Hybrid Electric Mobility: Design Considerations for Energy Storage Systems and Fuel Economy Optimization of Shared Semi-Autonomous Vehicles

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Recent trends show that consumers are shifting away from individually owned personal vehicles, and towards shared mobility solutions. Those who do own a vehicle are opting for those that are more fuel efficient and environmentally friendly. This thesis examines the design and vehicle development process of a shared semi-autonomous hybrid electric SUV to be deployed in a carsharing application, effectively addressing both established trends within the automotive industry and personalized transportation. The thesis directs the reader through each step of the vehicle design process starting with Target Market analysis, Component sizing, selection, and layout, and powertrain modeling and optimization, while highlighting how the primary design objective of fuel economy maximization guided the overall vehicle design.

Ultimately, this thesis aims to serve as a reference and knowledge transfer document to be used by members of the University of Waterloo Alternative Fuels Team as it pertains directly to the design of Energy Storage System utilized in the development vehicle, and therefore should be read by those involved with the project.

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To AVTC Organizers, Mentors, Faculty, Sponsors, and Students It has been a pleasure to work alongside such a passionate group of people. You have my gratitude and appreciation.

Dedication

To my family, friends, and colleagues, thank you for your unwavering support. This would not be possible without each and every one of you.

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List of Abbreviations

AAM	American Axle Manufacturing
ACC	Adpative Cruise Control
AEB	Automated Emergency Braking
A-ECMS	Adaptive-Equivalent Consumption Minimization Strategy
ALC	Automated Lane Change
AV	Autonomous Vehicles
AVTC	Advanced Vehicle Technology Competition
BEV	Battery Electric Vehicle
BMCU	Battery Management Control Unit
BMS	Battery Management System
CAN	Controller Area Network
CAV	Connected and Automated Vehicles
CSMS	Controls and Systems Modeling and Simulations
E&EC	Emissions and Energy Consumption
ECMS	Equivalent Consumption Minimization Strategy
EDU	Electronic Drive Unit
EMC	EcoCAR Mobility Challenge
ESS	Energy Storage System
EV	Electric Vehicle
FE	Fuel Economy
FTP	File Transfer Protocol Drive Cycle
HDS	Hybrid Design Services
HEV	Hybrid Electric Vehicle
HEV4	Malibu Hybrid Battery Pack
HMI	Human Machine Interfaces
HPPC	Hybrid Pulse Power Characterization
HWFET	Highway Fuel Economy Cycle
ICE	Internal Combustion Engine
LKA	Lane Keep Assist
LMU	Local Monitoring Unit
MaaS	Mobility as a Service

MPC	Model Predictive Control
MPG	Miles per Gallon
NHTSA	National Highway Transportation Traffic Safety Administration
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
PCC	Predictive Cruise Control
PHEV	Plug-in Hybrid Electric Vehicle
PSI	Propulsion System Integration
SAV	Shared Autonomous Vehicle
SOC	State of Charge
UWAFT	University of Waterloo Alternative Fuels Team
VDP	Vehicle Design Process
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled
VTS	Vehicle Technical Specifications
ZEV	Zero Emission Vehicle

For My Family

Chapter 1

Introduction

The transportation sector, more specifically, automotive industry, is one that can be characterized by its well-defined historical trends. These trends provide meaningful insight into the various socio-economic factors and implications surrounding historical events, with each established trend serving as an indicator which reflects the direct manifestation of consequences resulting from; new technology developments, government mandates, varying regulations, environmental concerns, or change in the global economic status. Furthermore, these indicators often align with the shifting landscape and changing values, wants, and needs of the target market.

Recent trends show that the current market of consumers is shifting away from away from individually owned personal vehicles, with those who do own a vehicle opting for those that are more fuel efficient and environmentally friendly. These ideals have proven to be the catalyst leading to the advent and adoption of shared mobility solutions such as car-sharing, ridesharing, and other mobility on demand platforms, all of which can be encapsulated by the Mobility as a Service (MaaS) paradigm.

Increased regulations on emissions standards have also led to the gradual decline in popularity of fossil fuel powered Internal Combustion Engine (ICE) vehicles, while Electric Vehicles (EV) and other Zero Emission

Vehicles (ZEV) are becoming increasingly more popular as an alternative. A growing number of federal governments around have announced aggressive timelines for the elimination of non-ZEV vehicles leading to an unprecedented level of spending by global automakers to develop and procure EVs and battery technology. A 2019 report analyzing 29 global automakers revealed that the industry will spend a minimum of $300 billion in the development of EVs over the next 10 years [1].

Table 1-1: Global 100% ZEV Targets by nation [2]

Country	Targeted Date
Canada	2040
China	TBD*
France	2040
Germany	TBD*
1India	2030
Norway	2025
Netherlands	2030
Scotland	2032
United Kingdom	2040

*Country currently developing 100% ZEV sales target

Decreasing costs resulting from advancements in electrified powertrain technology have also led to the increased prevalence of EVs and Hybrid Electric Vehicles (HEVs) on the road. A 2018 report published by Bloomberg New Energy Finance states that electric cars will achieve price parity with gasoline vehicles by 2024 and become cheaper by 2025 [2]. Technology advancements have also empowered automakers to produce EVs and HEVs containing Energy Storage Systems (ESS) with substantially larger energy capacity then their previous generation counterparts all while maintaining the same, if not smaller physical package. This enhancement of energy density alleviates any range anxiety concerns that once plagued the EV segment. The proliferation of EV technology also extends beyond the vehicles itself.

Charging infrastructure technology has developed at a pace matching, if not exceeding the development of the vehicles themselves offering faster charge times and more charging locations around the world. Gone are the days of the owner of an EV worrying if their car hand enough State of Charge (SOC) to make it to the next charging station or if they would have to hitch a ride home.

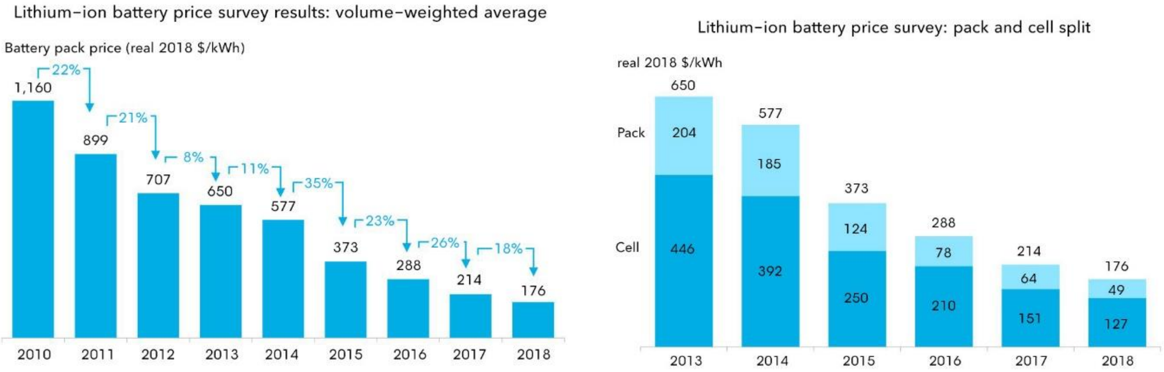


Figure 1: Historical Battery Pack Price ($/kWh) [3]

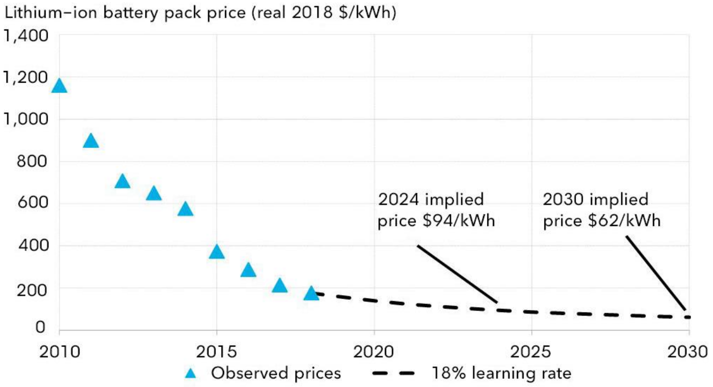


Figure 2: Lithium-ion battery pack price forecast [3]

Furthermore, there has been a distinct dissipation of the stigma that was once associated with EVs and HEVs. Not long ago the consensus was that electrified vehicles were a simple fad which existed simply for the sake of appeasing the "tree-hugging" environmentalists. With little to no performance benefits over conventional combustion vehicles, and stylization that often-resembled “Small Clown Cars”, early EVs were shunned by automotive industry, journalists, and enthusiasts alike. In short, EV’s were forecasted to disappear as quickly as they arrived. This notion quite clearly couldn’t be further from the truth. Today’s electrified vehicles have penetrated every market segment of the automotive industry. From Pick-Up trucks, to delivery vans, to luxury sedans, to utility vehicles, an EV currently exists on the market to suit any purpose. Electrification has also addressed the hyper-car realm. Porsche 918, Ferrari LaFerrari, Aston Martin Valkyrie, Koenigsegg Regera, Mercedes Project One, Rimac C2, and the NIO EP9, they all have two things in common; 1 – A price tag that would make those in the top 1% consider cheaper alternatives, and 2 – an electrified powertrain, proving that hybrids can deliver high performance.

Simply put, we are witnessing another transformative evolution within the automotive industry, the global shift to electric vehicles is now well and truly underway.

1.1 Thesis Objective

The objective of this thesis is to provide the reader with the theoretical knowledge and practical understanding on the process of developing a Hybrid Electric Vehicle Architecture that is optimized for Fuel Economy when deployed in shared mobility applications. Component selection, sizing, and layout for multiple viable designs and potential benefits and drawbacks for each are all examined within the context of this thesis. Ultimately, this thesis aims to serve as a reference and knowledge transfer document to be used by members of the University of Waterloo Alternative Fuels Team as it pertains directly to the design of Energy Storage System utilized in the hybrid electric

Shared Semi-Autonomous Vehicle currently under development for the EcoCAR Mobility Challenge.

1.2 Thesis Outline

This thesis includes eight chapters inclusive of this introduction. These Chapters are grouped into sections that align with actual design and development timeline for the project. The development of the vehicle platform is discussed in Part I of the thesis. Components of this section are as follows:

CHAPTER 4	Application – provides the reader with a general overview of the University of Waterloo Alternative Fuels Team in addition the Advanced Vehicle Technology Competition (AVTC) series, specifically the EcoCAR Mobility Challenge (EMC) for which the Vehicle Platform is being developed.
CHAPTER 5	Powertrain Design and Optimization – details the specific process of arriving at the final HEV architecture selection for the development vehicle with additional emphasis placed on the ESS.

Part II provides a well-defined characterization of the fully developed vehicle.

CHAPTER 6	Battery Pack Development – provides a comprehensive review of the current design of the Battery ESS as of the time of writing. This includes a discussion on power and energy sizing calculations, cell selection, and mechanical packaging efforts.

CHAPTER 7	Vehicle Modeling and Simulation Results – depicts the Modeling environment and setup used to simulate real world performance to the vehicle.

Part III concludes this thesis with relevant discussions on the findings presented in Part II. Recommendations and initial plans for future work are also provided in CHAPTER 8.

Chapter 2
Background and Relevant Information

2.1 Electrified Powertrains

The terms Electrified Powertrain or Electrified Vehicle are typically used as an umbrella term which refers to several powertrain layouts that utilize electrical energy to produce and augment propulsive torque. Electrification within vehicles can take place in many different forms, the following sections will provide a high-level overview of the most common manifestation of electrified vehicles.

2.1.1 Mild Hybrid

Mild Hybrids, also known as Battery Assisted Hybrids, typically utilize an electric motor/generator in addition to a small battery pack to produce electrical energy which can be used to assist or boots the ICE output. In a mild hybrid the ICE is the primary power source. When coasting or cruising the vehicles engine can be used to spin the motor generator to create electrical energy. These types of vehicles typically do not have a dedicated driving mode that allows for propulsion via electrical power only, however the addition of electrification does lead a substantial reduction in fuel consumption in comparison to conventional internal combustion vehicles [4]. For example, Mild Hybrids can turn the engine off as the vehicle coasts down to a stop and can quickly turn the engine back on again when the driver attempts to accelerate. This Start/Stop functionality has been shown to result in up to a 7.8% improvement in fuel economy in urban environments [5].

2.1.2 Strong Hybrid

A Strong Hybrid also commonly referred to as Full Hybrid or simply Hybrid Electric Vehicle (HEV) uses a combination of an ICE and a battery powered electric motor to drive the vehicle. A dynamic control strategy is used to determine the optimum balance between the two propulsion sources at any given time depending on the driving scenario. HEVs will typically have a more complex vehicle architecture and physical packaging requirements than mild hybrids and conventional vehicles due to the multiple unique torque flows. This often results in a user-selectable drive mode such as Engine Only Mode, EV mode, and several hybrid dive modes. As with the Mild Hybrid, Strong Hybrid vehicles offer significant improvements in fuel consumption, but also offer overall performance that is on par, if not superior to a comparable conventional vehicle.

2.1.3 Plug-in Hybrid

Plugin-Hybrid Electric Vehicles (PHEVs) are similar in nature to HEVs, maintaining all the same benefits in comparison to a traditional vehicle. The main distinction between a PHEV and HEV can be found in the PHEV larger capacity battery pack. The larger battery pack found in the PHEV traditionally allows for a much large EV only range when compared to HEV's.

Furthermore, a PHEV battery pack directly from grid electricity via a plug-in charger.

2.1.4 Battery Electric Vehicles

The Battery Electric Vehicle (BEV) does not have an engine or any of the related internal combustion components. Instead, BEVs solely rely on the battery powered electric motors to provide propulsive torque to the wheels. BEV's have become known for their characteristic strong acceleration performance due to the instantaneous torque provided by the electric motors. Like the PHEV, the BEV's can also be recharged via a plug-in charger.

2.2 Hybrid Vehicle Configurations

From a vehicle architecture standpoint, HEV's can be classified as one of three categories; Series, Parallel, or Series-Parallel Split. These categories refer to the vehicles overall power flow and torque path layout. Each of these categories is defined in the following sections.

2.2.1 Series

In a Series HEV the engine's sole purpose is to convert potential energy in the form of fuel to mechanical power. The engine is not capable of providing propulsive torque to drive the wheels. The mechanical power generated by the engine is then converted to electrical energy via a motor/generator. This same electrical power is used to propel the motor via a motor. Thus, the internal combustion and traction electric vehicle systems in a Series HEV are isolated from one another. This isolation allows for engine speed to be controlled independently from vehicle speed, meaning the vehicle's control algorithm could be tuned such that the engine runs at the optimal speed to minimize losses incurred in the electricity generation process [6] [7].

The electric motor used to drive the vehicle can receive power via the engine-generator pair or electrical power directly from the vehicles battery pack as shown in Figure 3 [6].

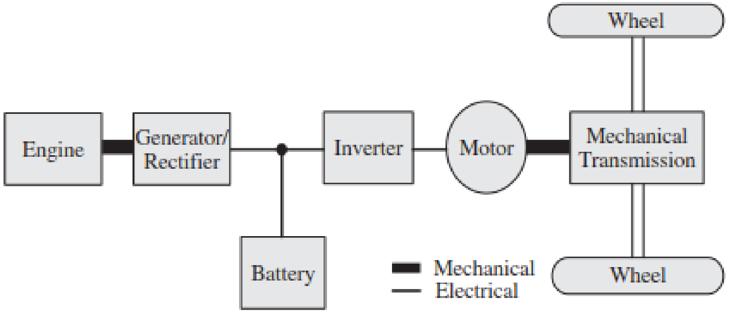


Figure 3: Example Series HEV architecture [6]

2.2.2 Parallel

In a Parallel HEV drivetrain, the engine provides propulsive torque to the driven wheels similar to a conventional vehicle. An electric motor is mechanically coupled to the driveline allowing it to boost the engine's power output. The mechanical coupler is used to add the produced torques from the engine and motor and deliver the resulting torque to the driven wheels. Thus, the engine and motor torque can be controlled individually, however the speeds of the engine, motor have a fixed relation to overall vehicle speed. Figure 4 depicts a bloc diagram representation of the mechanical coupling. In a Parallel HEV, the ICE is connected to 1, the motor to port 2, and the driven wheels to port 3. An example Parallel HEV architecture layout can be seen in Figure 5.

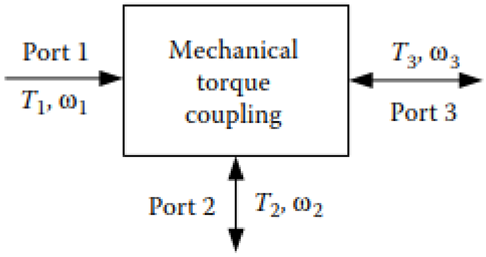


Figure 4: Mechanical Coupler Block Diagram [8]

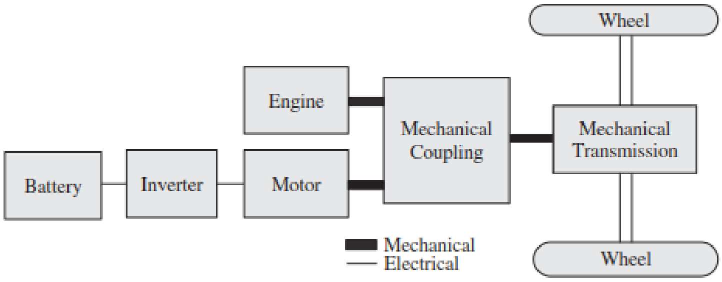


Figure 5: Example Parallel HEV architecture [6]

Table 2-1 provides a summary of the drive modes available in the series and parallel architectures in addition to the conditions required enter the given mode.

Table 2-1: Architecture Vehicle mode summary [6]

Vehicle Mode	Series	Parallel
Electric Vehicle	When the battery has sufficient energy, and the vehicle power demand is low, the I/G set is turned off, and the vehicle is powered by the battery only	When the battery has sufficient energy, and the vehicle power demand is low, then the engine is turned off, and the vehicle is powered by the motor and battery only.
Combined Power	At high power demands, the I/G set is turned on and the battery also supplies power to the electric motor.	At high power demand, the engine is turned on and the motor also supplies power to the wheels.
Engine Only	During highway cruising and at moderately high-power demands, the I/G set is turned on. The battery is neither charged nor discharged. This is mostly due to the fact that the battery' s state of charge (SOC) is already at a high level but the power demand of the vehicle prevents the engine from turning, or it may not be efficient to turn the engine off	During highway cruising and at moderately high-power demands, the engine provides all the power needed to drive the vehicle. The motor remains idle. This is mostly due to the fact that the battery SOC is already at a high level, but the power demand of the vehicle prevents the engine from turning off, or it may not be efficient to turn the engine off.
Power Split	When the I/G is turned on, the vehicle power demand is below the I/G optimum power, and the battery SOC is low, then a portion of the I/G power is used to charge the battery	When the engine is on, but the vehicle power demand is low and the battery SOC is also low, then a portion of the engine power is converted to electricity by the motor to charge the battery.
Stationary Charging	The battery is charged from the I/G power without the vehicle being driven.	The battery is charged by running the motor as a generator and driven by the engine, without the vehicle being driven.

2.2.3 Series-Parallel Split

The Series-Parallel layout, shown in Figure 6, represents the most complex configuration as it allows for both Series and Parallel driveline functionality, optimizing the vehicle for various driving scenarios [7]. This is facilitated via a disconnecting mechanical coupling that can connect or disconnect the output of the engine from the vehicle's final drive.

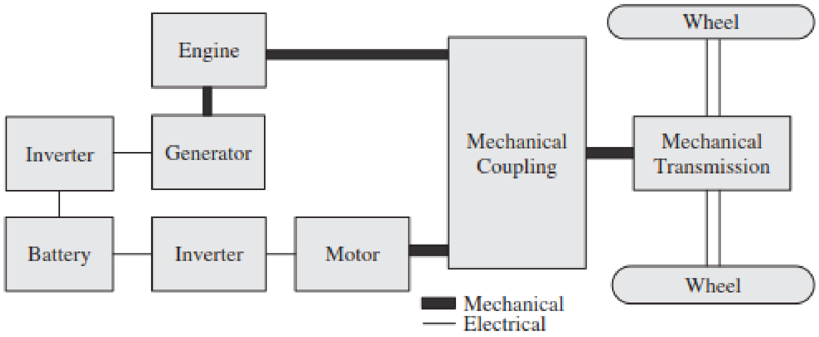


Figure 6: Example Series- Parallel architecture [6]

2.3 Motor Placement

As mentioned in previous sections, electric motors can be placed in several locations within the vehicle architecture to facilitate a certain purpose or meet packaging constraints. Within hybrid electric vehicle architectures, electric motors can be reference based on their position in the vehicle as shown in Figure 7. A P0 motor is connected to the engine's accessory belt, a P1 motor to the engine crankshaft, P2 motors are located pre-transmission, whereas P3 motors are located post-transmission. P4 motors are located directly on axle to propel the driven wheels of the vehicle.

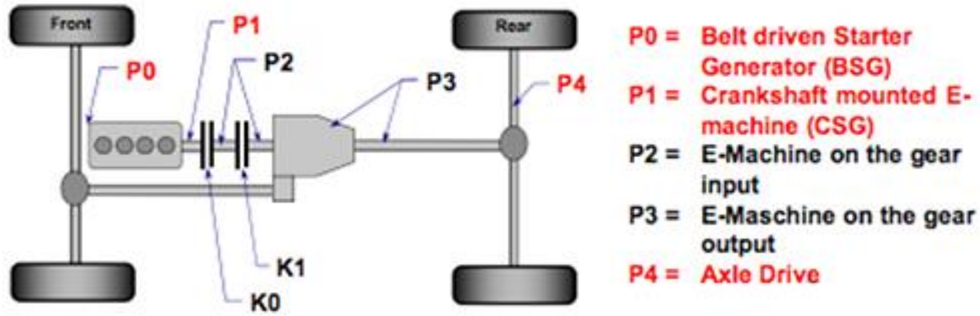


Figure 7: Electric Motor Position designation [9]

2.4 Automated Driving

Besides powertrain electrification, road vehicle automation is arguably the most revolutionary trend within the automotive industry [10]. Autonomous vehicles (AVs) are poised to dramatically alter transportation as we currently know it. In 2016 the National Highway Transportation Traffic Safety Administration (NHTSA) reported 37,461 fatalities as a resulting from vehicle crashes in the United States [11]. This represented a 5.6% increase over the previous year and a 14.4% increase over 2014 vehicle collision related fatalities. This is a problem the global automakers plan to address via the introduction of autonomous driving technology.

From increased safety to congestion relief, experts are continually discovering new applications in both the public and private sector that will benefit from the addition of innovative autonomous driving technology. Such technologies include but are not limited to: Automated Emergency Braking (AEB), Adaptive Cruise Control (ACC), Automated Lane Change (ALC), Lane Keep Assist (LKA), Blind Spot Monitoring, Automated Parking, Front/Rear

Collision Warning, Driver Drowsiness Detection, and Occupant Detection. The Society of Automotive Engineers has defined a standard for six independent levels of automation as displayed in Table 2-1

Table 2-1: SAE Automation Levels (J3016)

SAE Level		Name	Definition
Human driver monitors the driving environment	0	No Automation	Zero autonomy; the driver performs all driving tasks
	1	Driver Assistance	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.
	2	Partial Automation	Vehicle has combined automated functions (acceleration and steering) but the driver must remain engaged with the driving task and monitor the environment at all times.
Automated driving system monitors the driving environment	3	Conditional Automation	Driver is a necessity, but nor required to monitor the environment. The driver must be ready to take control of the vehicle at all times with notice.
	4	High Automation	The vehicle is capable of performing all driving functions under certain conditions. The driver may have the option to control the vehicle
	5	Full Automation	The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

2.5 Advanced Vehicle Technology Competition Series

Since 1988, the U.S. Department of Energy has sponsored Advanced Vehicle Technology Competitions in partnership with the North American automotive industry. Managed by Argonne National Laboratory, AVTCs provide a platform to develop the next generation of engineers and business leaders who will address future energy and transportation challenges. [12] [13]

With opportunities for undergraduate and graduate students from various disciplines including engineering, business, project management and communications, AVTCs challenge students beyond the traditional classroom environment. Participants re-engineer a donated production vehicle to improve energy efficiency and to meet the toughest emissions standards. Teams also aim to maintain features will that make the vehicle attractive to the customer; performance, consumer acceptability, safety, and cost. Students apply their theoretical knowledge to not only solve complex engineering problems, but also learn valuable leadership, project management skills, public relations, marketing and business development skills. More than 20,000 students from 93 educational institutions in North America have participated, gaining real-world, hands-on experience tackling the challenges associated with building fuel-efficient vehicles while integrating advance vehicle technologies [13].

2.6 University of Waterloo Alternative Fuels Team

The University of Waterloo Alternative Fuels Team (UWAFT) is a student-led advanced vehicle technology research and development group based out of the University of Waterloo. UWAFT has participated in seven AVTCs since being established in 1996. The team is currently operated out of the University of Waterloo’s Sedra Student Design Centre with access to a fully equipped vehicle garage, vehicle lift, office space, 4-wheel chassis dynamometer, and multiple powertrain test-cells.

Chapter 3
Literature Review

As the market share for shared mobility transportation solutions continues to grow within urban environments, increased research efforts are documenting potential implications, evidence of long-term sustainability, or lack thereof. The following provides a brief overview of literature analyzing current developments, potential impacts, and future potential of carsharing as a shared mobility solution in addition to autonomous vehicle implications on fuel economy.

Literature has shown that on-demand mobility can provide numerous transportation, land-use, environmental, and social benefits. Moreover, users of shared mobility solutions tend to have reduced vehicle ownership and annual Vehicle Miles/Kilometers Travelled (VMT/VKT) rates [14] [15]. At its core most carsharing operations share a set of common goals; Reduced traffic congestion, Reduced personal vehicle ownership, Increasing mobility options in low income markets, Reducing VMT, Reducing emissions, facilitating more efficient land use, and providing more accessibility among transportation modes [16]. These goals can be used to evaluate the overall success and long-term viability of carsharing and shared mobility. D.J. Fagnant et al. conducted a study simulating low level market penetration of Shared Autonomous Vehicles (SAV) in the 12mi x 24mi regional core of Austin, Texas. With only

1.3% of all regional trips completed by SAV, the study concluded that each SAV can replace approximately 10 conventional within the designated area while maintaining a reasonable level of service. However, this also results in a 8% increase in VMT as SAVs may often need to complete "no-passenger trips" in order to reach the next traveler, or relocate to a more favorable position [17]. In contrast M.W. Levin reports that tens of thousands of SAVs would be required in order to fully replace personal vehicles leading to significant congestion and wait times during peak hour demand [18]. W. Zhang et al. suggests that SAVs could pave way for the elimination of up to 90% of parking demand by customers who adopt the shared mobility solutions at the low market penetration rate of 2% [19]. In terms of growth, research of active North American carsharing operations conducted by S.A. Shaeen et al. reveals that 6.9% and 12.5% of individuals over the age of 21 in Canada and the United States respectively are active members of, or have used a carsharing service [16]. This number increases dramatically with the inclusion of the post-secondary (University/College) market (18-21). Ultimately the literature reviewed implies that while carsharing continues to gain popularity and market share, increased education, impact evaluation, and supportive policy approaches are required to facilitate the ongoing expansion and development for this emerging mode of transportation [15]. Furthermore, combing shared mobility and vehicle autonomy will amplify the adoption of both technologies.

AVs are well on track to become an emergent phenomenon by 2020, accepted technology by 2030, and dominate the personal transportation industry by 2050 [14]. If AVs are to become ubiquitous, then SAVs will need to meet, if not exceed various characteristics of today's conventional vehicle, most importantly safety and fuel economy. At the time of writing a standardized fuel economy testing method for AVs does not exist. Current US fuel economy testing consist of a vehicle on a chassis dynamometer with a human driver following a pre-set drive trace or velocity schedule. Thus this standardized testing system neglects differences in how individuals drive their vehicles on the road, nor does it account for the significant impact AVs may have on fuel economy [20]. It has been shown that AVs algorithms designed without considerations for efficiency can result in a 3% reduction of fuel economy, while efficiency focused strategies may be result in fuel economy improvements of up to 10% [20] [21].

A.C. Mersky et al. formulated the "Automated Vehicle Drive Cycle" using the existing FTP and HWFET cycles in order to provide a standardized fuel economy testing method that captures the impacts of automated driving. The Automated Vehicle Drive Cycle is intended to be incorporated within the standardized EPA weighted tested scheme for Fuel Economy and emissions. One such efficiency-oriented strategy is developed in C. Wu et al. where mathematical computation of the optimal acceleration/deceleration targets is found via the Lagrange multiplier method. These optimal values are then presented in a human readable fashion to the driver of the vehicle via the Human Machine Interface (HMI) in a driver operated vehicle, or directly result in automated actuation in autonomous driving conditions. Simulation results showed vehicles with the system consumed significantly less fuel than those without in all acceleration conditions (22-31% overall fuel savings) and most deceleration conditions (12-26% overall fuel savings) [22]. Another method presented in B. Asadi et al. proposed the utilization of upcoming traffic signal information within the vehicle's adaptive cruise control system to reduce idle time at stop lights and fuel consumption [23]. The developed algorithm relied on Model Predictive Control (MPC) to formulate a Predictive Cruise Controller (PCC). When active, this control strategy led to a 47% reduction in fuel consumption and 56% less CO_2 emission in comparison to the conventional baseline ACC controller [23].

PART I:

Platform Development

Chapter 4

Application

The 12th AVTC, the EcoCAR Mobility Challenge recognizes the ongoing shift in the automotive industry, specifically in relation to shared mobility and vehicle autonomy, and aims to utilizes its status as the premier collegiate automotive engineering student design competition as a platform to educate those who will continue to further this change. Thus, the development of the vehicle as examined in this thesis is pertinent as it represents an accurate reflection of the current state of the automotive industry.

4.1 The EcoCAR Mobility Challenge

The EcoCAR Mobility Challenge tasks 12 North American universities to apply advanced propulsion systems, electrification, SAE Level 2 automation, and vehicle connectivity to improve the energy efficiency of a 2019 Chevrolet Blazer – all while balancing factors such as emissions, safety and consumer acceptability. Teams will use onboard sensors and wirelessly communicated data from the vehicle's surrounding environment to improve overall operation in the connected urban environments of the future. The team's vehicles will include automated functions such longitudinal acceleration and steering. These automated functions must assume that the driver will be engaged in all driving task and must actively monitor the environment. In addition, EcoCAR teams will use Model-Based Design to effectively manage projects, collaborate on designs and develop complex embedded systems.

4.2 Vehicle Design Process

The Vehicle Design Process (VDP) set forth in the EcoCAR Mobility Challenge closely mirrors that of the design process used by global automotive manufacturers. Each of the four years, having a unique focus, goals, and milestones are set up to advance teams through the VDP as shown in Figure 8.

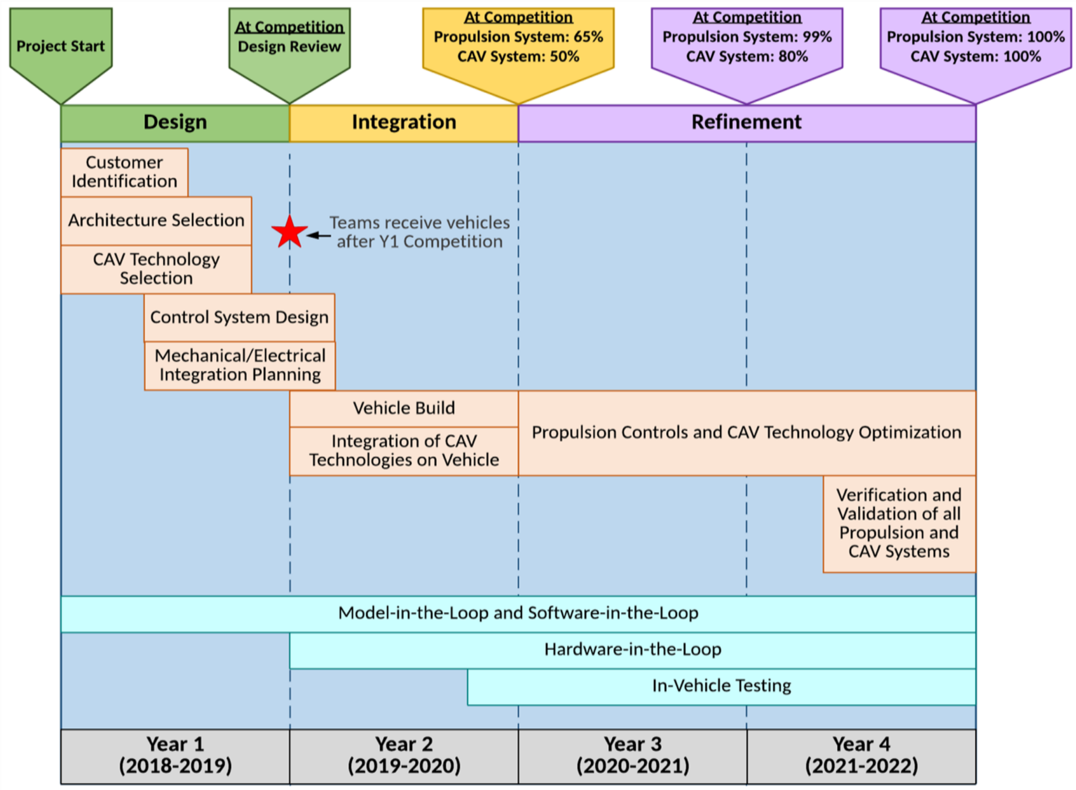


Figure 8: EMC Vehicle Design Process [14]

At the time of writing UWAFT has completed the first year of the VDP, primarily centered on the vehicle architecture design and selection and will be commencing propulsion system bench testing and powertrain integration.

Team's ability to achieve the primary technical goals will be assessed throughout the VDP via a series of static and dynamic events. Technical goals can be linked to one or more competition events as shown in Figure 9.

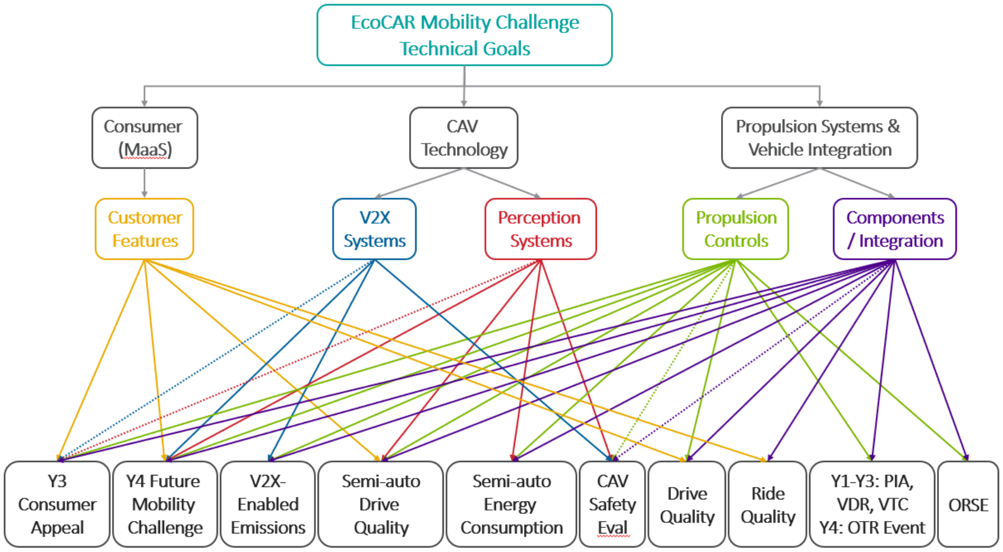


Figure 9: Technical Goal Evaluation Events [14]

4.3 Mobility as a Service (MaaS)

Mobility as a Service is a data-driven, consumer centered model of transportation that encompasses a combination of traditional transportation methods via a personalized on-demand, real time platform [25]. The overall success of MaaS implementations vary by region and can be influenced by factors such as urban geography, overall trip patterns, and quality/coverage of existing public transit infrastructure [26].

In general, the MaaS spectrum can be broken down into four distinct categories; Ridehailing, Ridesplitting, Ridesharing, and Carsharing. Table 2-2 provides an overview of each of the four categories and examples of services in each.

RIDEHAILING: A service that arranges one-time shared rides on short notice, usually through a smartphone app. Vehicles are typically privately owned [24].

RIDESPLITTING: Similar to ridehailing, however trips are pooled between multiple users heading to the same destinations, multiple destinations along the same route, or within close proximity to each other [24].

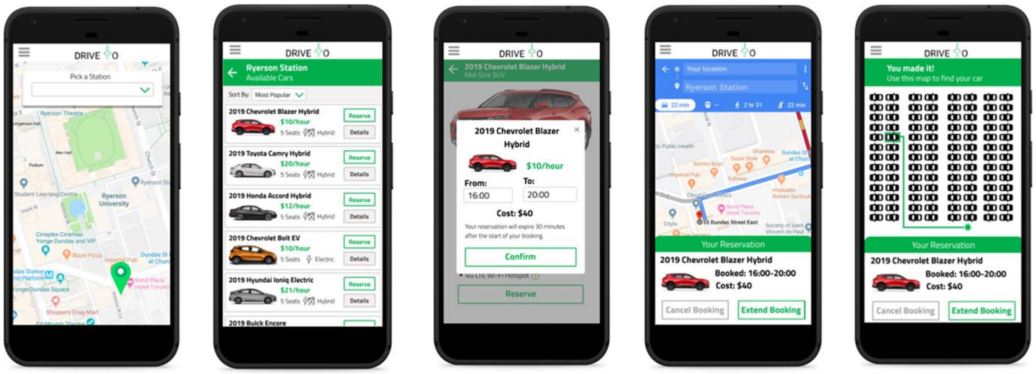
RIDESHARING: Similar to ridehailing, except the passenger(s) and driver share a common destination. Fundamentally, Ridesharing adds passengers to a pre-existing trip [24].

CARSHARING: A service that provides users with access to an automobile for short-term use. Vehicles can be deployed in a fleet-owned network or exist in a peer-to-peer ecosystem [24].

Table 2-2: MaaS Spectrum [16]

	Fleet-Owned	Privately Owned
Customer Drives	Carsharing: Maven, Car2Go, Zipcar	P2P Carsharing: Turo, Getaround, Maven
Customer Rides	Traditional taxi/Limo Service Future: robotaxi	Ridesharing: Tripda & Blablacar (Europe) Ridehailing: Uber, Lyft

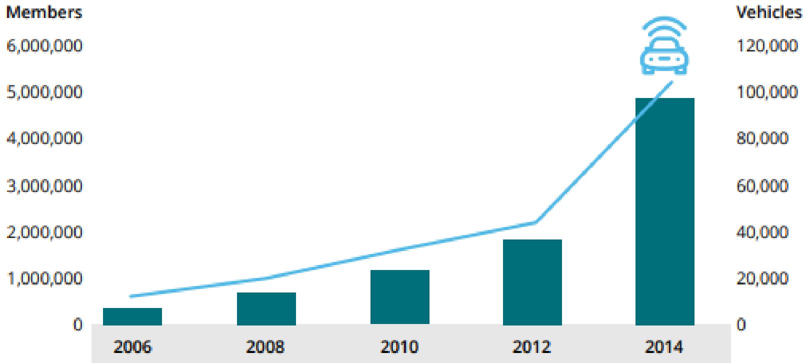
The development vehicle explored in this thesis has been designed specifically to be utilized in a Fleet-Owned car-sharing application, with each vehicle having a feature set geared towards semi-autonomous driving in addition to improving the overall driving experience. Unlike the traditional ownership model, users to are not introduced to new vehicle features by a dealership representative, nor do they have benefit of long-term vehicle ownership, allowing them to find features for themselves. Thus, it is imperative that MaaS aims to quickly establish user trust in the vehicle and its features. One method to do so involves clear communication of the vehicle overall feature set and functionality via a smart phone application, HMI, and other in cabin innovations.



Your reservation will expire 30 minutes after the start of your booking.

Figure 10: UWAFT MaaS Carshaing application [27]

MaaS has experienced a steady growth in adoption in recent years, this growth correlates with the continued global urbanization trends as larger percentage of the population relocates to urban environments each year [28].



	2006	2008	2010	2012	2014
■ Members	346,610	670,822	1,163,645	1,788,027	4,842,616
Membership growth rate		39%	32%	24%	65%
— Vehicles	11,501	19,403	31,967	43,554	104,125
Fleet growth rate		30%	28%	17%	55%
Member-vehicle ratio	30.1	34.6	36.4	41.1	46.5

Figure 11: Global Carsharing growth [28]

4.4 Target Market

Carsharing is typically concentrated in denser populated urban areas where a larger and more accessible customer base can be served [29]. In the United States in 2003, 94% of carsharing membership was concentrated in eight metropolitan areas – San Francisco, Los Angeles, San Diego, Portland, Seattle, Boston, New York and Washington D.C. [30]. A similar concentration exists in Canada and Europe [30]. The density in urban areas is found to be highly correlated to the decreased number of vehicles per household and vehicle distance travelled [30]. Lower vehicle ownership can be attributed to the scarcity of parking space along with better transit systems. Carsharing works best when used in conjunction with other modes of transportation, such as public transit, rather than replacing them. In a 2005 report, it was stated that nearly 20% of carsharing trips were accessed by transit [30]. Furthermore, city governments are more willing to mandate pro-carsharing initiatives in urban environments compared to suburban or rural communities that do not face the same issues. Vehicle congestion and pollution, two key issues commonly encountered in urban settings, are addressed by carsharing via reducing the number of vehicles on the road. Canadian studies suggested that 15% to 29% of customers sold a vehicle after joining a carsharing program, whereas 25% to 61% delayed or had forgone a vehicle purchase [15]. An example of city government initiatives is the Metro Vancouver 2040: Shaping our Future regional plan that prioritizes city efforts to increase carsharing prevalence [31].

4.4.1 Socioeconomic Characteristics

Consumers in younger age groups are more likely to become carsharing members compared to older demographics. The US carsharing customer market segments, outlined in Table 4-1, support this notion [29]. Older demographics are typically more skeptical shoppers and adopt new services, such as car sharing, much later than younger age groups [29].

Table 4-1: US carsharing Market Distribution Age [29]

Age Group (in Years)	Percentage of US Carsharing Market
18 – 24	24.5%
25 – 34	35.5%
35 – 44	25.0%
45 and Older	15.0%

Education also plays a significant factor in carsharing membership. University/college students and young professionals make up 60% of revenue in the carsharing industry with continued projected growth [2]. In addition, about 80% of carsharing consumers possess at least a bachelor's degree [2]. Higher education incurs significant tuition costs on its students, causing students to have relatively low disposable incomes, which is another factor relating to carsharing membership. Carsharing services typically partner with universities and colleges to implement their services on campus. For example, Zipcar is offered at 300 schools throughout the US while Enterprise CarShare is offered at 125 colleges and universities [2]. Regarding gender, there is no significant difference between the number of female and male members of current carsharing services.

4.4.2 Psychographic Characteristics

A survey conducted by UWAFT gave helpful insight on the psychographic characteristics for the personality traits, values, attitudes, interests, and lifestyle choices of the customer. The respondents were asked whether they would want to become/stay a member of a carsharing service. If yes, they were asked for reasons for why they would want to become a member. The most popular responses are presented in Figure 12 [32]

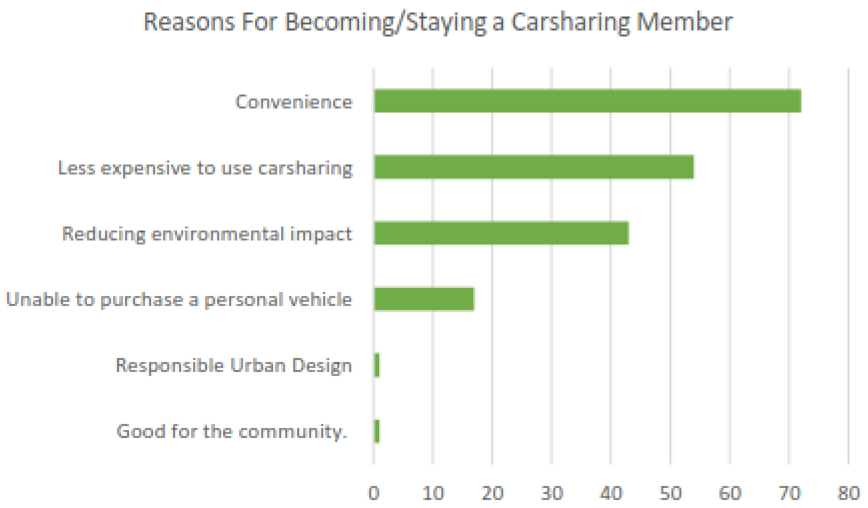


Figure 12: Survey Results for question "What are your reasons for wanting to become/stay a member?" (Select all that apply) [32]

Convenience is the most common reason for becoming a carsharing customer as it allows users to enjoy the mobility of operating a vehicle while not having to deal with insurance, maintenance, and long-term parking. In a carsharing study, 60.0% of the carsharing customers surveyed said that they use the service because it 'saves time' [33]. The ability to acquire a vehicle as quickly as possible is what sets carsharing apart from other rental vehicles and is what its customers value most.

4.4.3 Fleet Owner Definition

In order to obtain a year-round customer base, the target market will include two unique customer segments; university/college students, and young professionals (those who have recently graduated from post-secondary education). The carsharing fleet will function as part of a station-based service but with only round-trip use. One-way trips pose an operational issue if vehicles are shifted around into areas with insufficient stations. The one-way option would require the number of stations to greatly exceed the number of fleet vehicles, which are difficult to obtain due to Toronto's lack of parking spaces. The one-way trip use case is better suited for other MaaS services such as public transit or ridesharing.

Multiple carsharing companies were interviewed to gain a better understanding of carsharing from a fleet owner's perspective. As a result, the vehicle wants and needs of the fleet-owner will be defined as reliability, usability, and ownership cost; ownership costs encompass its purchase price, maintenance, repairs, insurance and fuel. This ownership cost better encompasses the needs of a fleet owner, whose primary goal is to be net profitable overall.

4.4.4 Customer Definition

The customer segments of university/college students (18-24) and young professionals (25-35) create an overall age bracket accounting for 60% of the overall market [29]. The education of the target customer would involve pursuing or possessing a college/university degree. The income of the young professionals would be between $40,000 and $70,000 while the income of students would still be less than $9,999. These recent graduates lack in disposable income, compared to older age groups, due to having been in the workforce for only a short period of time. This customer segment tends to have less children, are unlikely to own a vehicle and are more open to new technologies; all characteristics of typical carsharing members [29].

The use cases of the customer segment include running errands, moving furniture, shopping for groceries, going to entertainment venues and inter-city round trips. Commuting will not be a common use case. From a carsharing user study, it was found that carsharing members tend to be more concerned with environmental and social issues [30]. They tend to be willing to try out new ideas and find saving money very important [30]. Members are more concerned with the functionality of the vehicle than the vehicle as a reflection of their personality or status [30]. These personality traits allow carsharing members to surpass the barrier of entering an unfamiliar vehicle if it means they can make an environmental impact while saving money compared to owning a personal vehicle.

The general wants and needs of the customer of the carsharing service will include vehicle range, cargo space, passenger sears, safety, handling and usability.

Chapter 5
Powertrain Design and Optimization

Knowing the intended target market, use case, and overall application of the vehicle as defined in the previous chapter, allowed UWAFT to formulate a conceptual design for the vehicle propulsion system platform. The team went through several design iteration and optimization cycles in order to achieve high-level targets and objectives. This chapter details this powertrain design and optimization process including objectives, limitations, performance targets, and an overview of the final selected architecture.

5.1 Objectives and Performance Metrics

As with most of projects of this nature, the first step in the designing the vehicle propulsion system architecture typically involves establishing design objectives and evaluation criteria used to measure each potential design's ability to achieve its intended purpose. Ownership Cost, Vehicle Technical Specifications, and Integration risk were established as the key performance indicators used in the propulsion system evaluation method. Analysis for each of these metrics is given in the following sections.

5.1.1 Ownership Cost

Total ownership cost of the vehicle is one of the most important items which must be taken into consideration from a fleet-owners perspective. Global automakers place great emphasis on the study cost optimization as the results of this effort significantly influence not only profit margins, but also determines market size and composition of those who could feasibly afford the vehicle. Luxury automotive manufactures can afford to spend more time and resources on engineering development, exotic materials, and artisanal assembly processes as they cater to the extremely rich who are able to pay for such. Thus, lower quantities of the vehicle are produced. If the same company were to market the same vehicle to the typical middle-class citizens, the company is likely to lose an exorbitant amount of money. In short, the vehicle must be designed in a way such that the cost can be sustained by the target market.

This requirement also applies within the context of the prototype vehicle under development by UWAFT. The overall cost must be appropriate for the carsharing application in which it will be deployed as it represents a key barrier of acceptance of advanced vehicle technologies. Both the fleet owner and customer prioritize lower cost vehicles. Fleet owners seeks a reduction in purchase price, maintenance costs, and fuel costs while maximizing resale value, and the customer seeks an overall reduction in the cost to use the carsharing service. The following equations were used for the purpose of evaluating the associated total ownership cost for each to the proposed vehicle architectures

$$Total\ Ownership\ Cost = (Purchase\ Price) + (Total\ Fuel\ Cost) - (Resale\ Price) \tag{5.1}$$

$$Total\ Fuel\ Cost = \frac{Fuel\ Price\left[\frac{\$}{gal}\right] * Liftime\ Mileage\ [mi]}{Fuel\ Economy\ [mpg]} \tag{5.2}$$

$$Resale\ Price = Purchase\ Price * (100\% - Depreciation) \tag{5.3}$$

Where,

1. Lifetime miles (mi) is assumed to be 30,000 miles over a period of 18 months
2. Energy Consumption (mpg) will be based on actual vehicle energy consumption data
3. Fuel Price ($/gal) is on average EIA projections (Regular gasoline: $3.19/gal | Premium gasoline ($3.74/gal) as shown in Figure 13.

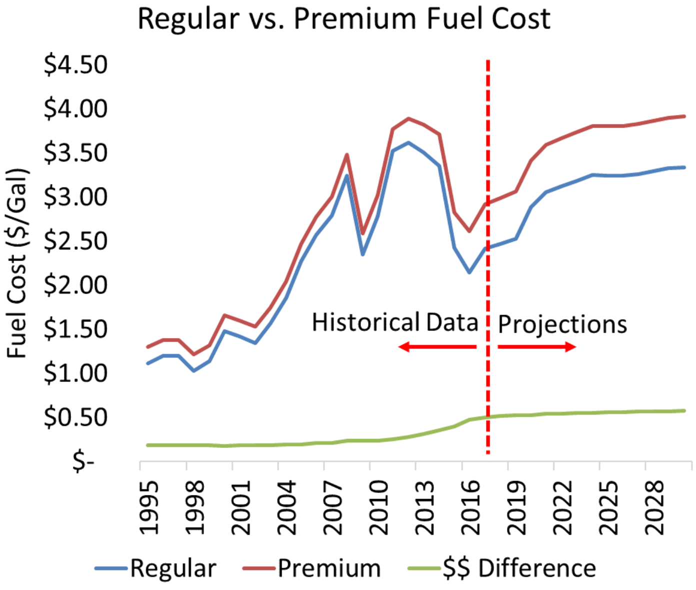


Figure 13: EIA Fuel Price Projections [25]

In addition,

$$Purchase\ Price = (PropSysCost) - (Stock\ PropSysCost) \qquad 5.4$$

$$PropSysCost = (Motor\ Cost) + (Battery\ Cost) + (Engine\ Cost) \qquad 5.5$$

Where,

1. $Motor\ Cost$ is valued at \$6/kW per the 10s peak power discharge rating of the motor and inverter system.
2. $Battery\ Cost$ is valued at \$20/kW per the 10s peak power discharge rating high voltage energy storage system.

Finally,

$$EngCost_{SI} = 827 + (109 * NoCyl) + (6.2 * EngPwr) + (283 * DI) + (1730 * Boost) \qquad 5.6$$

Where,

1. $NoCyl$ = Number of Engine Cylinders
2. $EngPwr$ = Rated Peak Power (kW)
3. DI = Direct Injected (Binary)
4. $Boost$ = Turbocharged/Supercharged (Binary)

5.1.2 Vehicle Technical Specifications

The technical specifications of the vehicle, otherwise known as VTS, was also used to evaluate each of the proposed vehicle architectures in terms of overall performance. Table 5-1 lists all VTS metrics evaluated via computational modeling and simulation alongside mandated minimum safety requirements and competition targets.

Table 5-1: VTS Specification Table [25]

VTS Specification	Units	Competition Target	Min. Performance Requirement
Acceleration IVM-60mph	s	7	9
Acceleration 50-70mph	s	6.5	TBD
Braking 60-0mph	ft	138.4	N/A
Cargo Capacity	ft^3	Stock	7.6
Passenger Capacity	$Persons$	5	5
Curb Mass	kg	N/A	N/A
Starting Time	s	<=2	<=5
Ground Clearance	$in.$	N/A	7.0
Total Range	$mi.$	250	200
Fuel Economy	mpg	33.5	Stock
Emissions	g/mi	Stock	Stock
Gradeability	% @ 60mph for 20 mins	N/A	3.5

5.1.3 Integration Risk

Finally, Integration Risk and the probability of successful execution was taken into consideration. UWAFT's benefits from its prior experience in EcoCAR competitions and aims to develop architectures that will see faster development cycles instead of pursuing over the top architecture ideas that prove not only difficult to implement, but also tough to troubleshoot and advance as vehicle development progresses. A balance is struck between the level of difficulty the team will experience during development and the confidence the team possesses in meeting the overall VTS specifications during the architecture implementation phase. This allows UWAFT to spend more time and energy focusing on executing the vision of the competition, primarily ensuring that CAV and Controls and Systems Modeling and Simulations (CSMS) groups do not face development curtailment due to mechanical integration bottlenecks [35].

UWAFT intends to maintain a low to moderate appetite for risk as it has elected to focus its integration efforts in the electric powertrain located in the rear of the vehicle only. This strategy ensures that the vehicle should experience minimal downtime during the propulsion system integration phase, as the internal combustion system, will take significantly less time to integrate and can be developed in isolation to the EV system. Considering this development philosophy, UWAFT developed a comprehensive risk assessment and analysis, the full extent of which can be found in the appendix of this thesis.

5.2 Propulsion System Requirements and Limitations

Several technical requirements and limitations influenced the design of the vehicles propulsion system. These constraints were imposed in order to ensure the creation of viable propulsion system designs that address the core vision of the EMC by satisfying rules, participating in dynamic events, and avoiding penalties, while still allowing for a level of uniqueness between teams. Figure 14 depicts the resulting product development process. Proper understanding and analysis of the design space/constraints are critical to successful vehicle development. Key propulsion system requirements and limitations are listed below:

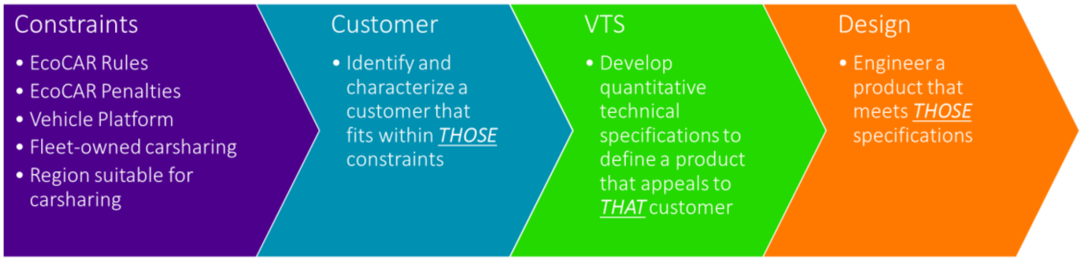


Figure 14: EcoCAR Product Development Process [25]

1. Hybrid System Design – The propulsion system design must not contain a hybrid propulsion system from another production vehicle in its entirety.
2. GM Powecube – A non-modified GM Powercube (engine - transmission pair) must be utilized in the team propulsion system design. The engine and transmission cannot be separated in any way in order to facilitate the integration of electric motor(s) in between.
3. Stock Engine – The propulsion system design must not include the 3.6L V6 engine that ships with the stock 2019 Blazer RS trim specification.
4. Fuel Tank Capacity – Fuel tanks must not have a capacity over 10 gallons.
5. Energy Storage System – The propulsion system design must incorporate a single non-team-built “Black-box” ESS. The ESS cannot be a hybrid energy storage solution, and not included multiple ESS’s connected in series or parallel.
6. Safety Requirements – The designed vehicle propulsion system must meet all minimum safety requirements and regulations.
7. Architecture Approval – P0 and P0-P4 powertrain designs have been pre-approved by the EcoCAR organizing committee.

Table 5-2: Overview of powercube options

	Engine			Transmission			
	Code	Engine Displacement	Intake System	Code	Gears	Acc* [Y/N]	ETRS** [Y/N]
1	LYX	1.5L	Turbocharged	M3U	9	Y	Y
2	LTG	**2.0L**	Turbocharged	M3D	9	Y	N
3	LTG	2.0L	Turbocharged	M3E	9	N	N
4	LTG	2.0L	Turbocharged	M3H	9	Y	Y
5	LCV	2.5L	Naturally Aspirated	M3D	9	Y	N

*Accumulator

**Electronic Transmission Range Selection

5.3 UWAFT VTS Targets

UWAFT's Team selected VTS targets are show in Table 5-3. These selections stemmed from information gathered on the general wants/needs of the customer and fleet-owner in additional to historical utilization data from fleet vehicles.

Table 5-3: UWAFT Defined Vehicle Technical Specifications

VTS Specification	Units	Competition Target	Min. Req	UWAFT Target
Acceleration IVM-60mph	s	7	9	5.5
Acceleration 50-70mph	s	**6.5**	TBD	5.8
Braking 60-0mph	ft	138.4	N/A	158.2
Cargo Capacity	ft^3	Stock	7.6	Stock
Passenger Capacity	$Persons$	5	5	5
Curb Mass	kg	N/A	N/A	2100
Starting Time	s	<=2	<=5	<2
Ground Clearance	$in.$	N/A	7.0	8.89
Total Range	$mi.$	250	200	268.5
Fuel Economy	mpg	33.5	Stock	30.83
Gradeability	% @ 60mph for 20 mins	N/A	3.5	3.5

These technical specifications served as the high-level targets. Each viable propulsion system architecture would be designed in such a way to satisfy these specifications.

5.4 Decision Making Process

Over fifty viable vehicle powertrain architectures were conceptualized during the design ideation phase, however only a total of 14 unique architectures fully evaluated. These remaining architectures can be distilled into four distinct categories; P0, P0-P4, P4, and Dual Motor designs as shown in Figure 15.

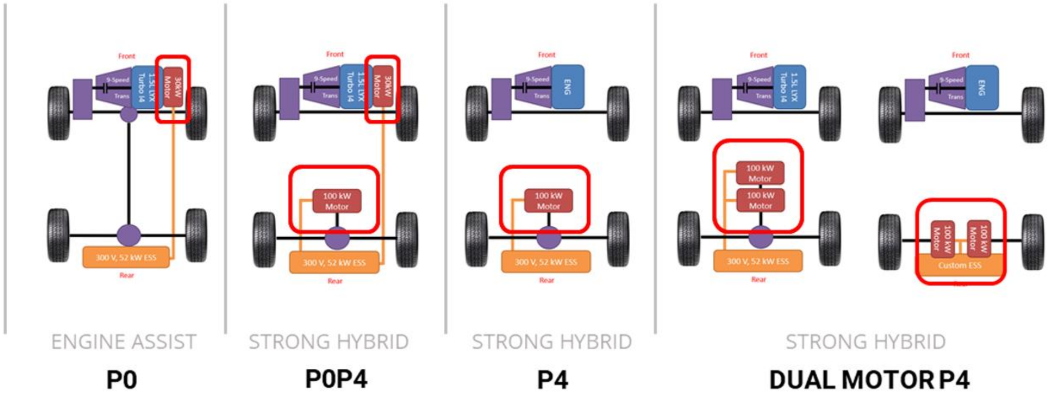


Figure 15: Viable Powertrain Architectures

P2 and P3 based designs were excluded from the list of viable candidates as the result of a “first-pass filter” algorithm. The filter assessed the controls development and mechanical/electrical Propulsion System Integration (PSI) risk associated with each of the considered architectures. A boundary condition was established such that any architecture with an associated risk score lower than the boundary was deemed acceptable. Architectures with an associated risk score higher than the boundary condition were eliminated from consideration.

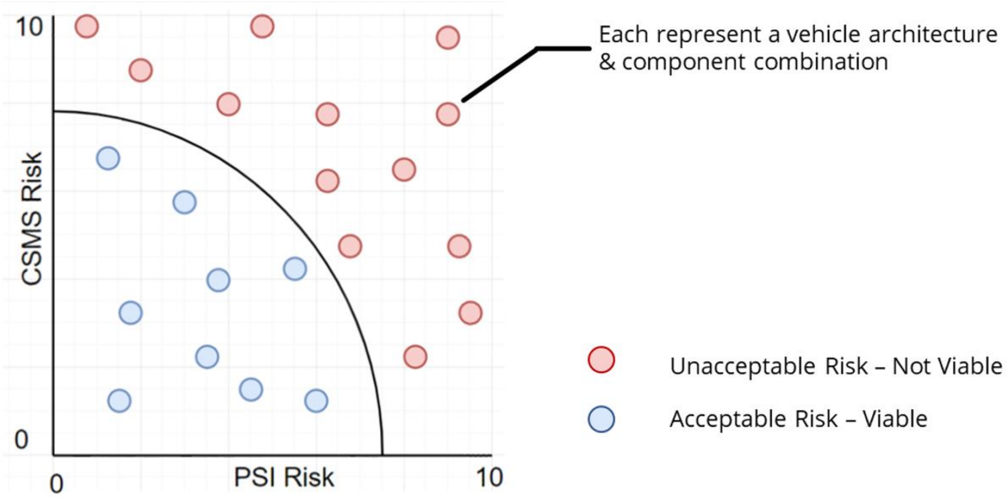


Figure 16: First-Pass Filter

A data-driven decision-making process was utilized in order to select the final propulsion systems architecture to be implemented from the remaining candidates. As mentioned in section 5.1 Cost, VTS performance, and integration risk were utilized as the primary factors within architecture evaluation function as shown.

$$F = 1.5 * Risk + VTS + 0.5 * Cost \tag{5.7}$$

The results of the evaluation function were compiled to form a weighted decision matrix as shown in the Appendix.

5.5 Final Architecture Selection

A P4 Parallel Hybrid shown in Figure 17 was chosen as the final architecture selection. This architecture was chosen as it embodied the optimal solution to the cost-risk-performance problem as outlined in section 5.1. From a high-level perspective, this design consists of; a 150kW electric motor with an integrated

9.04:1 gear reduction, also known as an Electronic Drive Unit (EDU) from American Axle Manufacturing, a 2.5 Liter inline-4 engine from General Motors, and a custom fabricated ESS provided by Hybrid Design Services (HDS). The selected architecture will also include a 12V start-stop system. Full powertrain component specifications are listed Table 5-4.

Figure 17: Selected Vehicle Architecture

Table 5-4: Component Specifications

Component	Manufacturer and Model	Performance Specifications	Vendor
Engine	2.5L LCV	151kW, 259Nm, 7000rpm	GM
Transmission	M3D GF9	7.6:1, no ETRS	GM
HV Battery	HDS Custom ESS	121kW, 5.5kWh, 346V	HDS
Motor	AAM EDU4	150kW, 9.04:1, 346Nm	AAM
Inverter	RMS PM150	50-400V, 150kVA	Rinehart

5.5.1 Vehicle Operating Modes

Under normal circumstances, the vehicle will be capable in operating in one of three drive modes; EV mode, Engine Only mode, or Parallel Drive Mode.

EV Mode – The vehicle will only utilize the electric powertrain, located in the rear of the vehicle, for short durations in situations where;

1. The torque demand is less the maximum output torque of the EDU.
2. The ESS SOC allows for sustained EV only operation.
3. A net-zero SOC change can be maintained due to a high number of potential regenerative braking events (City driving/Stop and Go traffic)

Engine Only Mode – In the event that electric propulsion becomes unavailable, the vehicle can still be driven as a conventional internal combustion vehicle. Operating the vehicle in this drive mode for sustained periods of time will lead to an overall reduction in fuel economy. Thus, this drive mode should be utilized as a fail-safe mechanism or at times during the integration phase where the EV system may not be fully operation, but the car may still be driven in order to collect data.

Parallel Drive Mode – The primary drive mode in which the vehicle will operate. This drive modes enables 4WD functionality while allowing the drive to extract maximum performance from the powertrain.

5.5.2 Motor Sizing and Selection

The EV powertrain, consisting of the Electric Motor and High Voltage Pack (ESS), must be designed with care to ensure that components are not only compatible with each other, but also satisfy the objective to produce a vehicle optimized for Fuel Economy. First, the power levels of the two systems should be matched such that the ESS discharge power capabilities meet the requirements of the motor as depicted in Figure 18 [36].

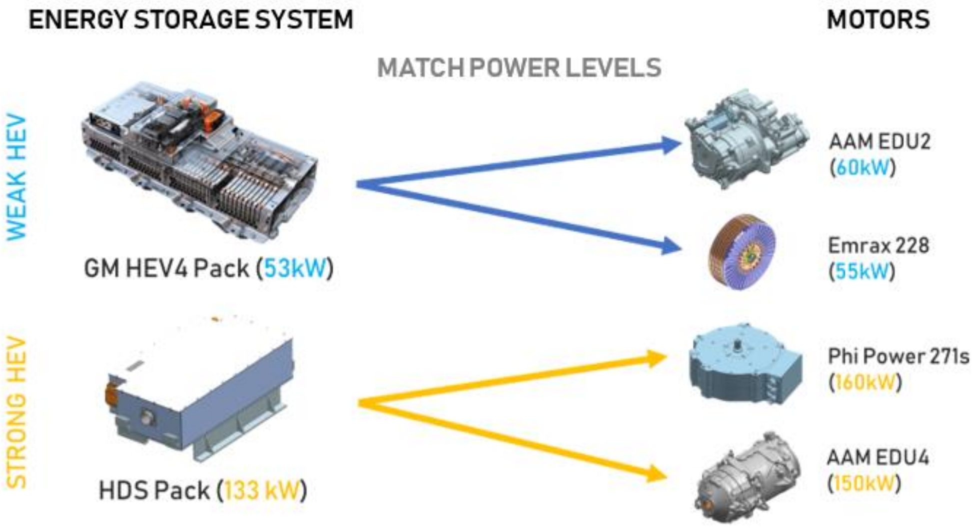


Figure 18: EV System Sizing [27]

Energy recovery potential should also be considered if the vehicle is to be designed to optimize for fuel economy. In order to maximize energy recovery, the vehicle should be designed such that regenerative braking is used as the primary means of slowing the vehicle. A maximum comfortable deceleration rate of $3.0 m/s^2$, as recommended Institute of Transportation Engineering, can be set as a target deceleration rate, however the charge capabilities of the ESS will typically act as the limiting factor determining how much energy can be realistically recovered through regenerative braking [36] [37]. Table 5-5 depicts

ESS regen capabilities for two ESS options considered while designing the EV powertrain for the Blazer.

Table 5-5: ESS Regen Capability [27]

Battery Pack	Peak Charge Rate	Battery-Limited Regen Speed
ESS A	65 kW	45.38 km/h
ESS B	133 kW	93.02 km/h

As shown, ESS B can bring the vehicle to a complete stop from 93.02 km/h using only regenerative braking at the targeted deceleration rate, whereas ESS A can only slow the vehicle from approximately 45 km/h before the application of mechanical brakes are required.

5.5.3 EV Acceleration and Top Speed

Next, the vehicle characteristics and specifications of the selected motor can be used to determine the expected EV acceleration capabilities and top vehicle speed. Using known constants such as the vehicle curb mass (2036.3 kg) and intended target 0-60mph acceleration time (5.5s), wheel radius (0.38m), and gear reduction ratio (9.04), we can find the torque required to meet the acceleration target.

$$a = \frac{v}{t} = \frac{27.78 m/s}{5.5\ s} = 5.05\ m/s^2 \tag{5.8}$$

$$F = ma \ => 2036.3kg * 5.05\frac{m}{s^2} = 10285.16\ N \tag{5.9}$$

$$\tau = 10285.16\ N * 0.38m = 3{,}908.36\ Nm \tag{5.10}$$

The AAM EDU4 has a peak torque rating of $346Nm * 9.04 = 3{,}127.84\ Nm$. Working in reverse, the EV only 0-60mph acceleration time can be found to be

$6.872s$. Although this does not meet the target acceleration time as stated in Table 5-1,this simple calculation gives provides UWAFT with a level of confidence that the target acceleration can be achieved when vehicle is being propelled by both the internal combustion and EV powertrains.

The maximum motor speed for the AAM EDU4 is listed as 13,146 rpm, accounting for the gear reduction the maximum speed at the half-shaft will be 1,454.2 rpm. Thus, the maximum vehicle speed can be found as shown below.

$$2\pi r = 2.39m \tag{5.11}$$

$$v_{max} = \frac{1{,}454.2\ rpm * 60 * 2.39m}{1000} = 208.53\ km/h \tag{5.12}$$

5.5.4 Engine Sizing and Selection

Finally, the known EV system and total ownership ship cost can be used to select the appropriate engine to be utilized in the vehicle architecture. Figure 19 shows two graphs used to compare powertrain options utilizing different engines. The vertical bars represent the total peak power of each powertrain configuration utilizing the 1.5L, 2.0L, and 2.5L engines respectively. In the scenario where a known 75kW EV system is used (left) in each configuration, the powertrain configuration containing the 2.0L engine will have the highest peak power output, and therefore outperform the other configurations. However, this configuration also has the highest associated ownership cost as denoted by the green line. The second-best performer in terms of peak output power, a configuration which utilizes the 2.5L engine, has the lowest cost of ownership

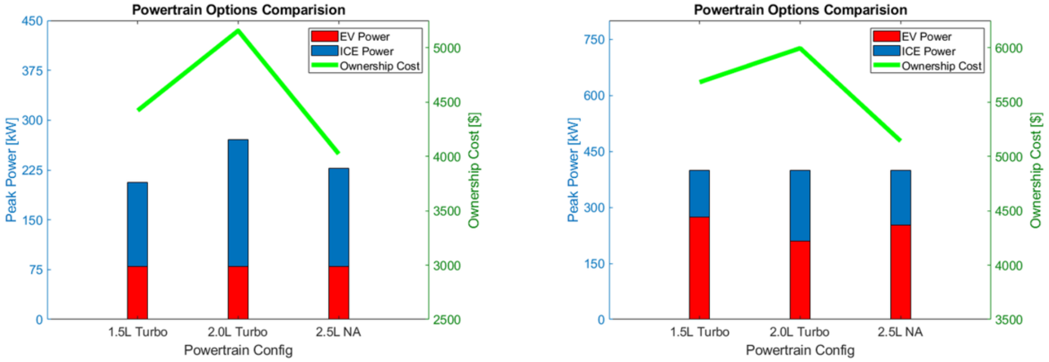


Figure 19: Powertrain option comparison. Fixed EV system (left) Supplemental EV system (right) [27]

The graph on the right assumes a set target peak power level. In this scenario the appropriate supplemental EV system is added to the engine power output in order to meet the overall power target. Once again, the 2.5L configuration was found to have the lowest cost of ownership. Thus, this engine was incorporated in the final propulsion system design.

Chapter 6
Battery Pack Development

As discussed in prior sections of this thesis, the primary design objective taken into consideration was to minimize fuel and overall energy consumption, thus it follows that the design of the UWAFT-designed Blazer's powertrain should be centered around the design of the battery pack. A collaborative effort which included UWAFT, Hybrid Design Services, and Ohio State University, was established in order to develop a custom energy storage solution for teams participating in EMC. This battery pack is the centerpiece of UWAFT's vehicle architecture design; thus, a significant effort has been invested in order to extract the maximum potential benefit from this custom component.

6.1 Project Specifications

VTS targets defined for the EcoCAR Emissions and Energy Consumption (E&EC) and 0-60 acceleration events were the driving factors behind the battery packs' electrical requirements. Target specifications for the project are displayed in Table 6-1.

Table 6-1: Target Specifications and Requirements

Requirement	Target	Unit
Pack Voltage	330 - 360	V
Continuous Power (Discharge)	75	kW
Rated Peak Power (Discharge, 30s)	> 80	kW
Useable Pack Energy	1.5-2	kWh
Total Pack Energy	5.5	kWh

6.2 Battery Pack Design

At the onset of the project two initial design concepts were formulated. Concept 1 involved re-engineering an in-production battery pack currently utilized in the current generation Chevrolet Malibu hybrid. Multiple Malibu hybrid (HEV4) batteries would be procured, disassembled, and re-packaged into a single black-box enclosure. This “combined” battery pack would unlock the possibility for various series-parallel cell and module configurations to facilitate battery pack options that meet different power and energy sizing requirements. Most importantly, the combined pack(s) would see overall improvements in nominal voltage, energy capacity, and peak discharge power when compared to the unmodified battery. A list of combined pack options is presented in Table 6-2.

Table 6-2: Combined pack options

Option	Nominal Voltage (V)	Energy Capacity (kWh)	Peak Discharge Power (kW)	Cell Count	Cell Config.	HEV4 Packs Req’ d
A	360	3.75	165.6	192	96S 2P	2.4
B	375	3.9	172.5	200	100S 2P	2.5
C	390	4.056	179.4	208	104S 2P	2.6
D	300	3.12	138	160	80S 2P	2

Concept 2 world require the development of an application-specific battery pack from the ground up by progressively advancing through the entire product development cycle. At a minimum, this effort would include tasks as stated in Table 6-3.

Table 6-3:Custom ESS Development Tasks

CUSTOM ESS DEVELOPMENT TASKS	
Project Planning	
System level technical specifications	
	Powertrain Modeling and System architecture selection
	Powertrain and Drivetrain Component Selection
ESS Specification Definition	
	Power and Energy Sizing
Cell Identification and Selection	
	Cell Identification
	Cell Testing and Thermal Manufacturing
	Cell/Pack Efficiency and Life (estimation)
	Cell/Pack Performance (estimation)
	Cell Selection
Module/Pack Design	
	Pack Interface Specification
	ESS Space Claim
	ESS Mechanical Design - Cell interconnection, Cell Packaging, HV/LV wiring, Thermal System
	ESS Thermal Design
	BMS Specification Definition
BMS Development	
	BMS System design
	Programming and Integration
	Interface and Functionality Documentation
Module /Pack Build	
	Pack Assembly
	EOL Testing
	Test Results and Analysis

Ultimately, UWAFT elected to proceed with concept 2 due to the OEM's hesitancy to support the re-engineer effort required for concept 1. The following sections of this thesis detail the current design of the battery pack at the time of writing.

6.2.1 Electrical Characteristics

Electrical characteristics and requirements for the battery pack were defined based on the simulation results of the E&EC and 0-60 acceleration events, further discussed in section 7.4. Table 6-4 shows maximum battery charge and discharge power for both city and highway drive cycles.

Table 6-4: Target Specifications and Requirements

EMC Drive Cycle	Max Discharge (kW)	Max Charge (kW)
City	108.29	46.585
Highway	108.292	93.185

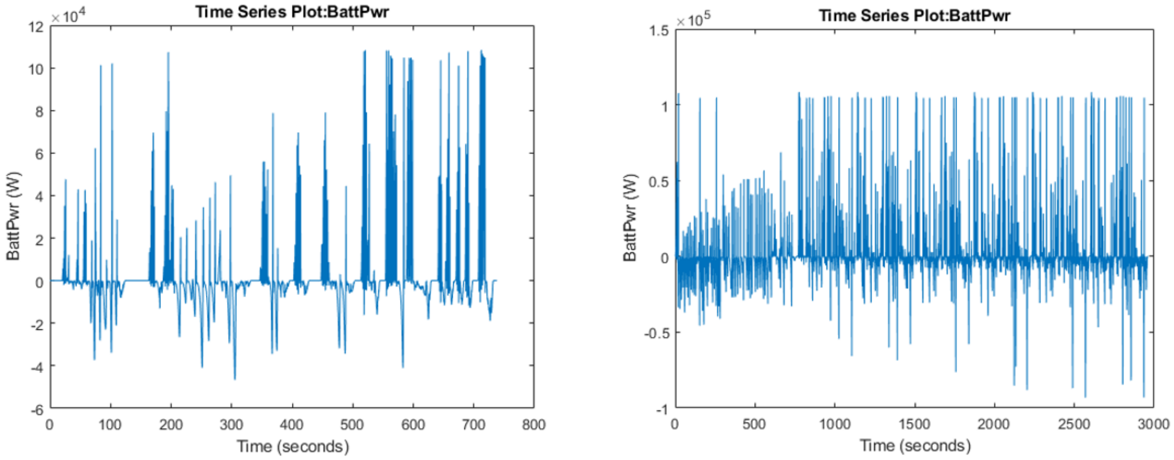


Figure 20: Drive cycle power consumption - City (left) Highway (right)

Adding a design buffer results in a target 30s peak charge and discharge power rating of 107kW and 120kW respectively. Pack energy sizing was completed via a similar process. A parametric sweep was used to find a useable energy capacity value that resulted a net-zero SOC depletion +/- 10% when staring from 60% SOC. A minimum useable energy of 1.2 - 1.5kWh was determined to be suitable.

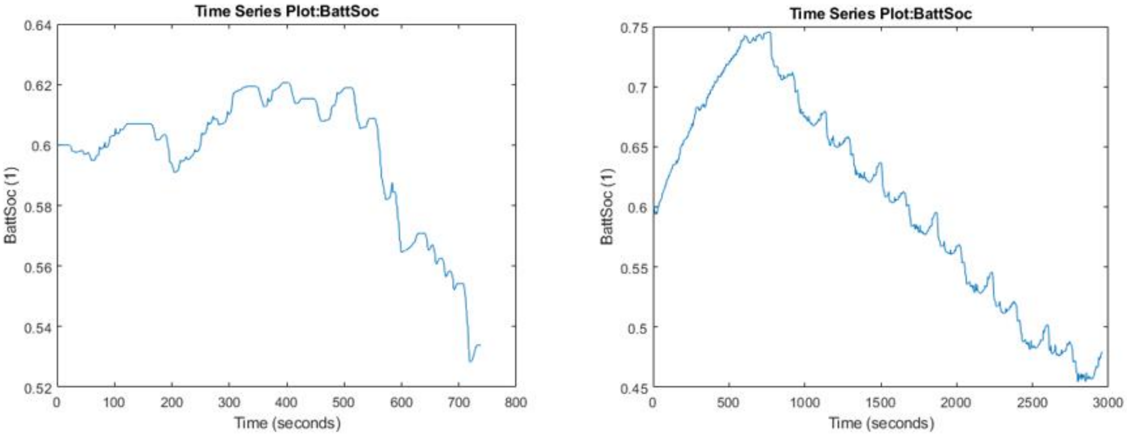
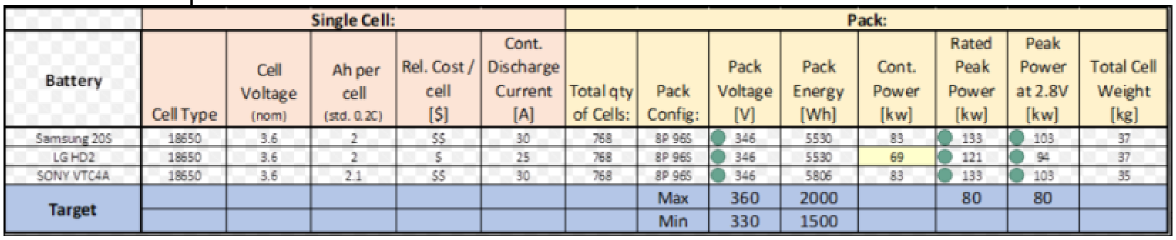


Figure 21: Drive cycle SOC depletion - City (left) Highway (right)

6.2.2 Cell Identification

Table 6-5 provides a list of the three cells and pack configurations considered. These are high-quality 18650-format cells which are readily available and meet or exceed the required power and energy targets. Furthermore, the 18650 form-factor is a well-characterized and well-developed cell, which allows flexible packaging options and allows the use of off-the-shelf components to assemble and weld the individual battery modules.

Table 6-5: Cell Options



	Single Cell:					Pack:							
Battery	Cell Type	Cell Voltage (nom)	Ah per cell (std. 0.2C)	Rel. Cost / cell [$]	Cont. Discharge Current [A]	Total qty of Cells:	Pack Config:	Pack Voltage [V]	Pack Energy [Wh]	Cont. Power [kw]	Rated Peak Power [kw]	Peak Power at 2.8V [kw]	Total Cell Weight [kg]
Samsung 20S	18650	3.6	2	$$	30	768	8P 96S	● 346	5530	83	● 133	● 103	37
LG HD2	18650	3.6	2	$	25	768	8P 96S	● 346	5530	69	● 121	● 94	37
SONY VTC4A	18650	3.6	2.1	$$	30	768	8P 96S	● 346	5806	83	● 133	● 103	35
Target							Max	360	2000		80	80	
							Min	330	1500				

The Samsung 20s cell was selected based on initial cell characterization and thermal test data received from HDS. Initial testing has revealed the Samsung 20s cells can sustain a continuous 40A discharge.

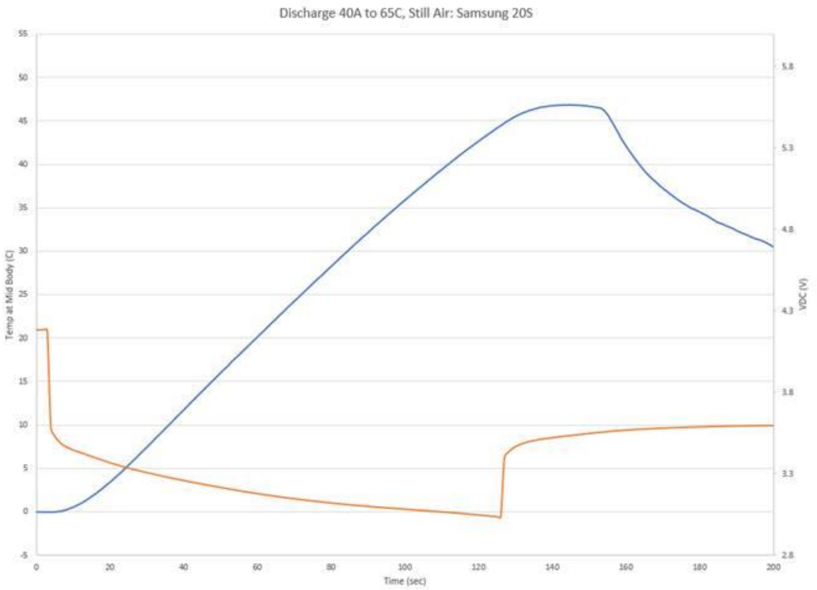


Figure 22: Continuous 40A Discharge - Samsung 20S

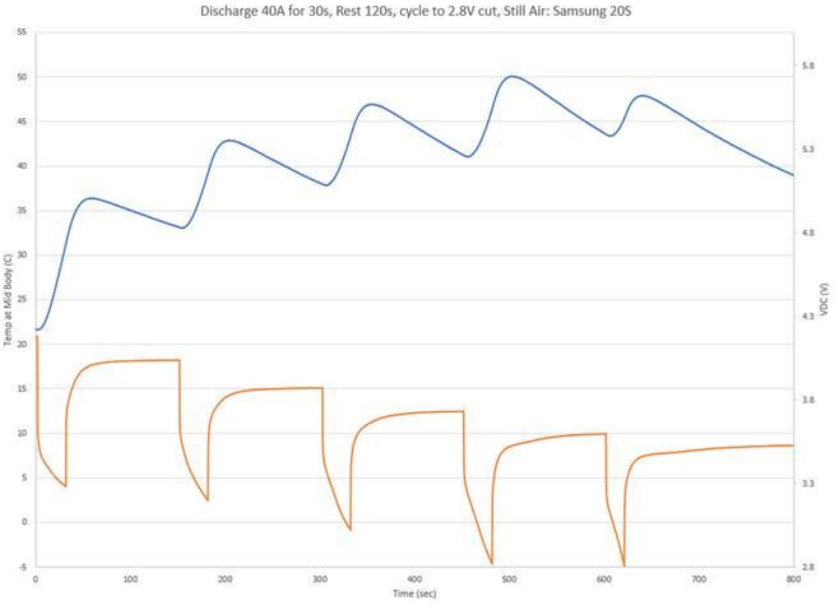


Figure 23: Repeated 40A Discharge - Samsung 20S

6.2.3 Battery Management System

The ESS will be actively monitored and managed by a fully integrated modular Battery Management System (BMS), this is done to reduce development costs while ensuring the BMS can be configured for the number of cells in series and allow for flexible Controller Area Network (CAN) communication. HDS will provide a LabView graphical user interface for monitoring of the cell information.

HDS is currently evaluating a system provided by Lithium Balance. The modular Lithium Balance LiBAL s-BMS consists of one master Battery Management Control Unit (BMCU) communicating with up to 32 Local Monitoring Units (LMU). Each LMU is capable of monitoring individual and total voltages for up to 3-8 cells in series, thus the intended 96S8P configuration will have a modular integrated BMS consisting of 13 boards (1 BCMU and 12 LMU's). The s-BMS system will be configured for active thermal management; however, HDS will provide teams with the ability to manually control the operation of the internal blower fan if desired. At a minimum, the BMS will report the following data via CAN messages:

- Pack Voltage
- Pack Current
- SOC
- Cell Voltage
- Cell Temperature (T_{min} & T_{max})

6.2.4 Thermal Design

The proposed pack will include an intake air interface, which draws air in from the cabin via an internal fan. The exact airflow requirements are still under development based on the cell usage cycle. HDS will provide further detail once the engineering is completed. The initial pack internal layout, including fan placement and cooling channels, can be seen in Figure 24. The exhaust air temperature is anticipated to rise slightly during high usage. The pack will include an exhaust-air port which must be routed outside the vehicle body. The exhaust must be directed to the exterior of the vehicle as the cells are in direct contact with the air stream. In the unlikely event that a cell ruptures or vents, the air cannot be reintroduced to the cabin.

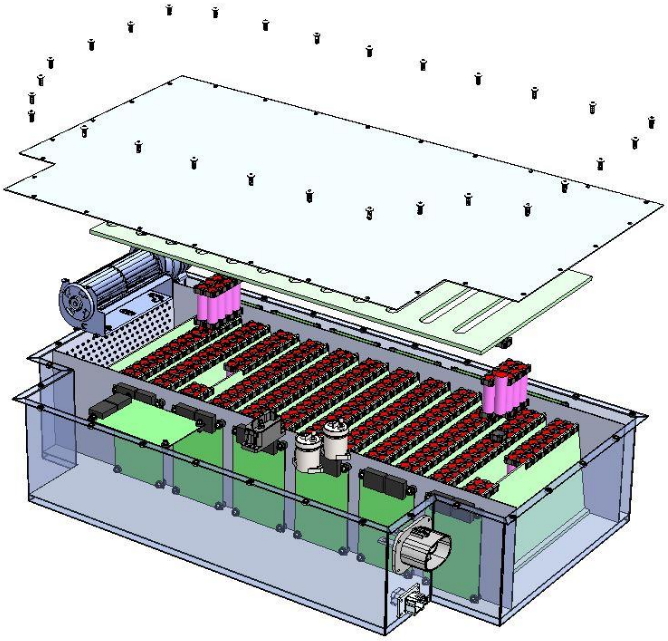


Figure 24:Preliminary Pack Internals Exploded ISO

6.2.5 Mechanical Packaging and Mounting

The exterior enclosure of the battery pack has been designed for installation in the area occupied by the spare wheel compartment in the stock vehicle. UWAFT will modifying the false floor in order to gain access to the area and successfully install the battery pack. An attempt was made to package the ESS underneath the vehicle body in the area which is occupied by the fuel tank in the stock vehicle. Packaging the ESS in this area would lower the vehicles center of gravity leading to improved vehicle dynamics and handling performance. However, this effort was ultimately abandoned due to the need for an additional skid plate, increasing the overall weight of the car, and overall poor serviceability.

The ESS will be securely held in position by the battery mount as shown in Figure 25 which has been designed with ease of fabrication in mind. Structural analysis of the design has yet to be completed.

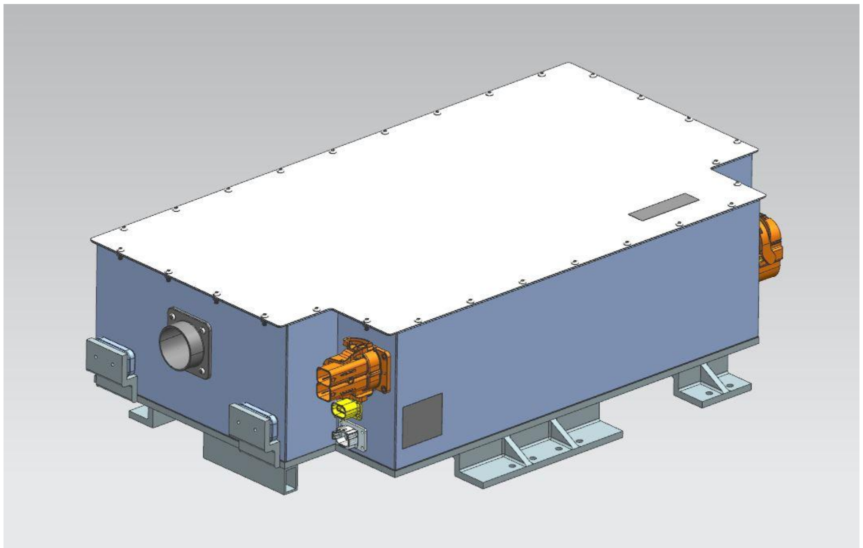


Figure 25: ESS and Battery Mount

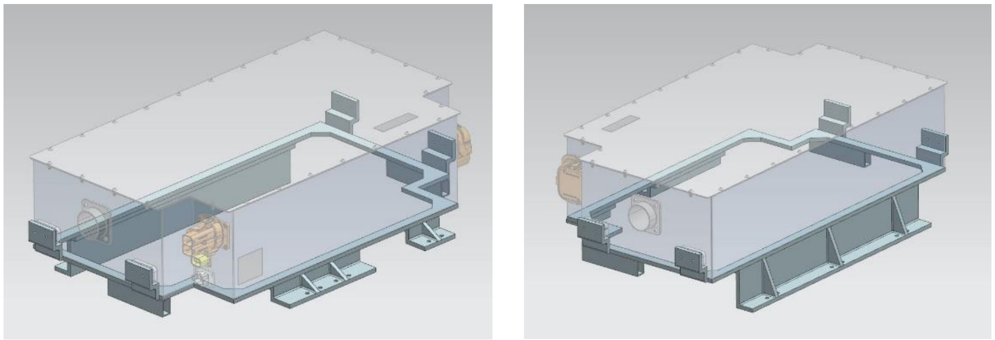


Figure 26: Battery Mount Isometric view - Front (Left) Rear (Right)

PART II:

Platform Characterization

Chapter 7
Vehicle Modeling and Simulation Results

The following sections of this thesis detail powertrain modeling and simulation environment setup, baseline performance results, and drive cycle analysis of the selected vehicle architecture. MathWorks MATLAB/Simlulink, a graphical programming interface for modeling, simulation, and analysis of multidomain dynamic systems, was utilized as the primary tool in the development of the powertrain model. With access to MATLAB library blocks and toolboxes, UWAFT is able to efficiently explore a large number of architectures containing different components in various configurations [38]. This rapid prototyping modeling and controls development process is essential to ensuring the identification of the optimal vehicle architecture for the EMC.

The propulsion system model is derived from a Simulink model for the stock 2019 Chevrolet Blazer provided by MathWorks. The model is composed of five unique subsystems; powertrain, drivetrain, controllers (Propulsion and CAVs), and driver input, as shown in Figure 27. These systems have been developed in parallel with component selection and architecture refinement in order to achieve the best results. MATLAB scripts were developed to facilitate dynamic loading of component data structures used to evaluate various architectures and perform component selection sweeps.

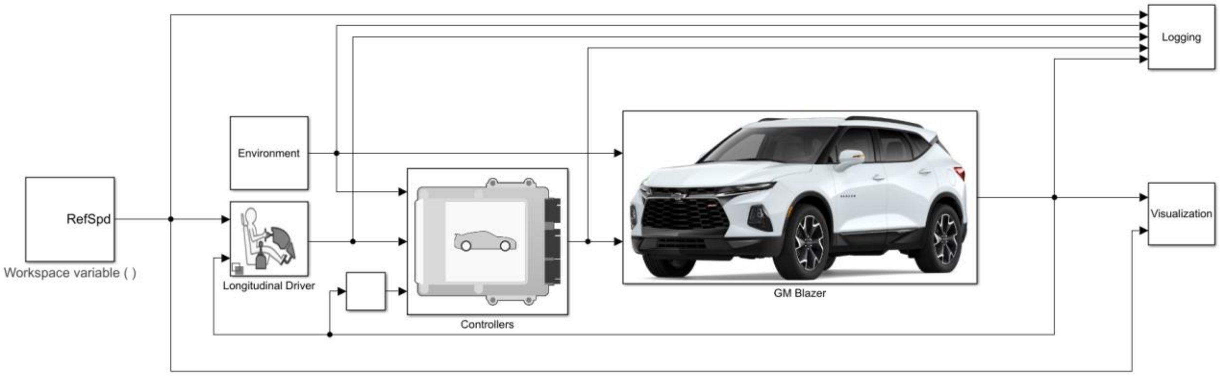


Figure 27: High level Vehicle Model (Simulink)

7.1 Powertrain Component Modeling

Basic building blocks from Simulink's powertrain block-set were used to develop accurate model representations of each component under consideration. The engine and motor models primarily rely on lookup tables generated via the Model-Based Calibration Toolbox [39] and simplified dynamics, whereas the ESS is represented as an equivalent circuit model. Linear interpolation between lookup tables breakpoints has been proven to be sufficient for standard drive cycle modeling [6].

7.1.1 Engine Model

The engine model is based on the mapped SI Engine block sourced from MathWorks [40]. This block uses a series of lookup tables to calculate the input speed and torque command. Significant lookup tables include the gas mass flow, fuel mass flow, exhaust manifold gas temperature, BSFC, HC, CO, NOx, CO2, and Pm Emissions. These emission calculations are further detailed by a set of blocks determining the level of filtrated emissions by an active/inactive catalyst. Actuator blocks use transfer functions to determine the actuator dynamics at a given time. These calculations assume that the operating pressure and temperature of the engine is constant and that the lookup table values are representative of practical applications [38].

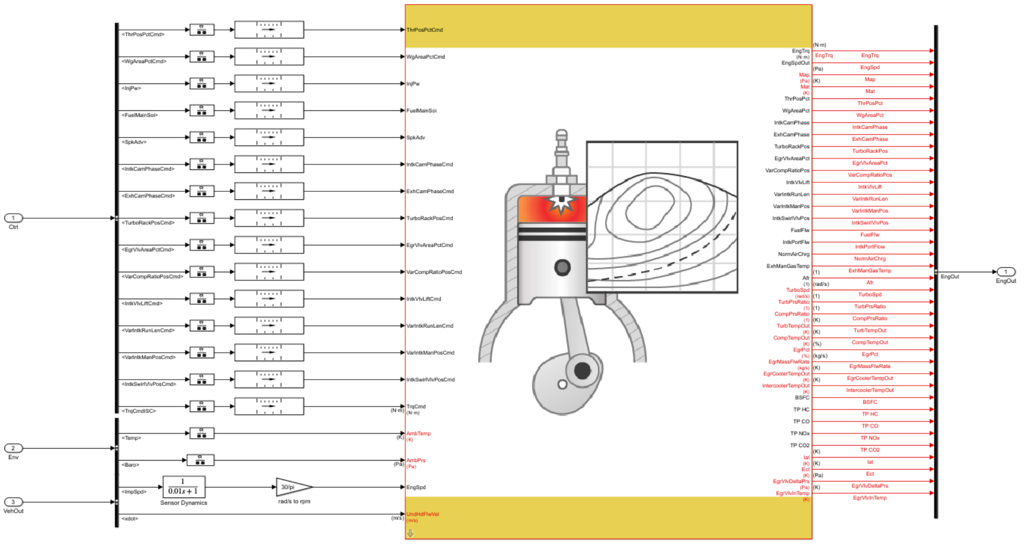


Figure 28: Simulink Engine Model

7.1.2 Battery Model

Similarly, the battery model is based on the MathWorks the Datasheet Battery block [41]. Physical parameters are calculated using the 0th-order equivalent circuit model. The block populates the open circuit voltage and the internal resistance via lookup tables in order to determine the battery output voltage. State of charge is calculated by coulomb counting. Temperature is assumed to be constant during operation, and the lookup table is assumed to be representative of battery conditions. These assumptions can be made as the changes in temperature are negligible during battery operation within the standard drive cycle. Equivalent circuit models have been shown to be sufficiently accurate for the purpose of battery voltage estimation however potential future improvements to the Battery model are discussed in section 8.2.1 [42].

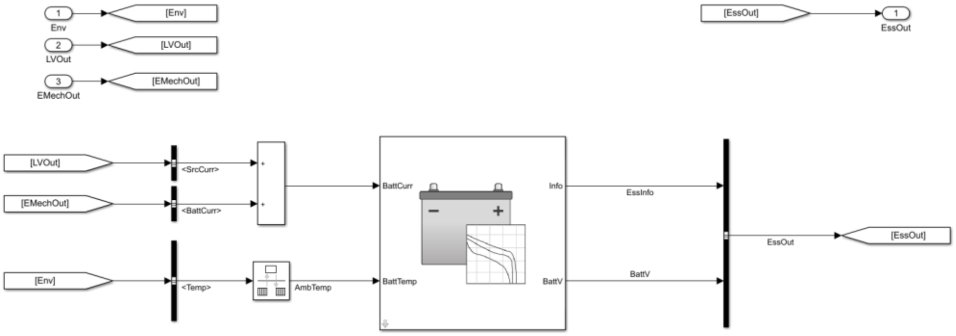


Figure 29: Simulink Battery Model

7.1.3 Motor Model

The motor model is derived from the MathWorks Mapped Motor model [43]. The model uses a lookup table to determine efficiency based on input torque and motor speed. Another lookup table uses maximum torque values and rotational speeds as tabulated torque-speed data. These lookup tables are populated based on data obtained directly from the Motor Manufacturer. Mechanical power is then calculated based on speed and torque. Current is calculated based on the battery voltage and the mechanical power. A gain is applied to the output torque to account for the integrated gearbox of the e-axle.

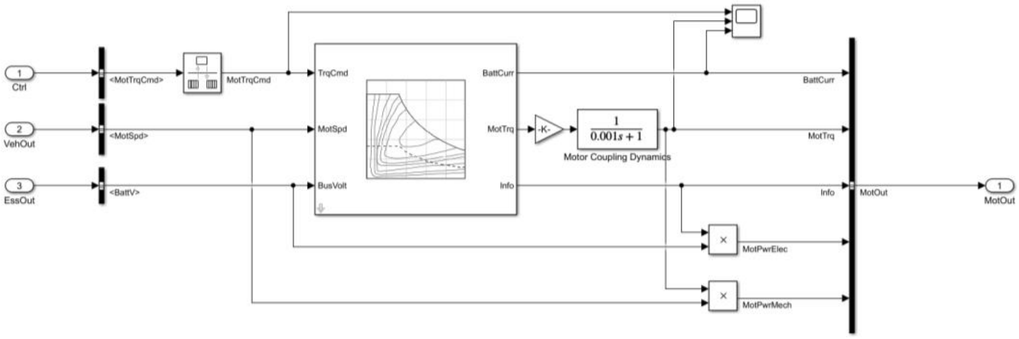


Figure 30: Simulink Mapped Motor Model

7.2 Energy Consumption Modeling

In a conventional vehicle, only low-level controls such as individual component controllers are utilized; high-level controls such as energy management strategies are not necessary. The driver's intent is communicated through the accelerator and brake pedals which are then translated into actions by the low-level executive component control. In a hybrid vehicle, however, an extra task is added to the vehicle controller, which is to determine how much power should be delivered by each of the energy sources in the vehicle [38]. Reasons for using an energy management strategy include the minimization of fuel consumption, maximizing battery life, reducing emissions, or reaching a suitable compromise among all of them [44]. A general example of a hybrid vehicle energy management system implementation is shown in Figure 31.

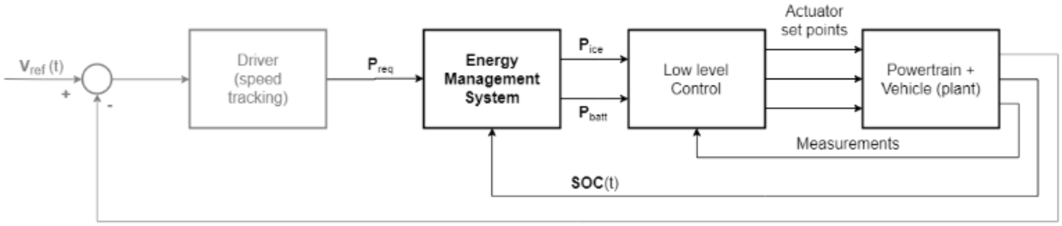


Figure 31: Example ECMS

Energy management systems dynamically manage the power flow allocation from each energy source to achieve the control objective. For the UWAFT-designed Blazer, the control objective is to minimize fuel consumption by optimizing a performance index, while satisfying global constraints such the final SOC value, SOC operating range, battery temperature, and battery power [44].

The Equivalent Consumption Minimization Strategy (ECMS) is a method that has been used widely in hybrid applications. The ECMS is based on the concept that the usage of the electric energy can be exchanged with the equivalent fuel consumption. The equivalence between the electric energy and the fuel energy is evaluated by considering the average energy paths leading from the fuel to the storage of electric energy [45]. The strategy functions as follows: for each time (t) with a time step of (Δt), parameters such as acceleration, speed, wheel speed and wheel torque are measured or evaluated. These values, along with the mentioned cumulative quantities are used to calculate a probability factor, which determines the equivalence factor. The equivalence factor finds the fuel equivalent of electrical energy based on whether the battery is being charged or discharged. This is used to determine the cost function. The cost function is found in a range of control variable values, and the control variable value that produces the lowest cost function is saved. This control variable then regulates the amount of torque that is provided by the electrical and fuel path. This is all done while considering global and local constraints such as final SOC and operating range of SOC, temperature and battery power [46]. Figure 32 shows the energy paths during discharge and charge in a hybrid vehicle. UWAFT will implement ECMS as it is a commonly used strategy with low computational complexity that has been proven to work well with hybrid applications. Simulation results are discussed in section 7.4.

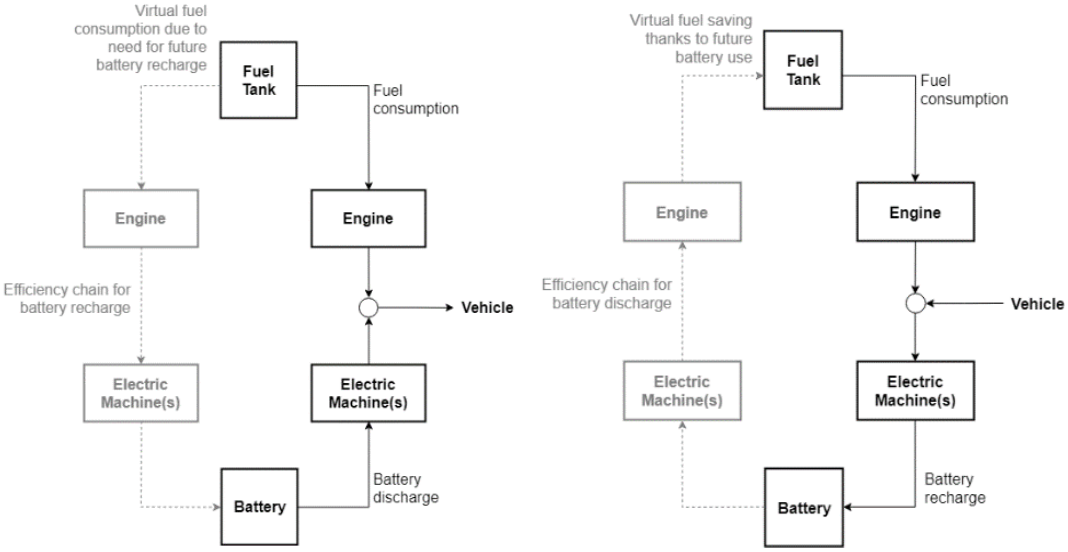


Figure 32: Energy Paths during discharge/charge in a HEV [38]

Since ECMS requires prior knowledge about the driving cycle, it cannot be used in real world driving scenarios. In order to add this functionality, an Adaptive ECMS (A-ECMS) control strategy is also included in vehicle model. As its name implies, this strategy is capable of adapting to dynamic driving conditions in real-time, however this additional functionality comes at a cost as some performance will be sacrificed in comparison to ECMS.

The resulting A-ECMS control action are derived from drive cycle prediction and driving pattern recognition. The “speed predictor” and “driving pattern recognition” blocks include a total of 24 unique parameters (average cycle velocity, positive acceleration, kinetic energy, stop time/total time, average acceleration, average grade, etc…) to store historical driving data. This method would only be implemented in the controller of the actual vehicle. Ultimately, an ECMS/A-ECMS strategy was selected as the energy management strategy for the vehicle’s propulsion system. This method is computationally efficient, mathematically proven and gives good energy consumption results, according to existing publications.

7.3 Model Limitations and Assumptions

As previously discussed, the primary powertrain components (motor, engine, and battery) have been modeled using lookup tables provided by the component manufacturers. Without the physical components to validate these tables, it has been assumed that these individual components have been modeled to a sufficiently high degree of accuracy. Additionally, the mechanical connections between components and through the whole driveline have been modeled based off thoroughly tested physical phenomena and can largely be assumed to be accurate. However, there exists some assumed parameters or conditions that may cause some variance in modeled fuel economy results [38].

Transmission shift time is one of those factors that may cause variance in the modeled fuel economy. A review of reference materials has revealed that vehicle shifting tends to range from a low of 50ms to approximately 500ms [23]. The initial shift time used in the model was 350ms. Different transmission shift times for the selected architecture were analyzed using the vehicle model resulting in a maximum fuel economy of 32.83 MPG, and a low of 32.19 MPG as shown in Figure 33. Overall, the fuel economy is not significantly correlated with shift time, with the maximum difference being around 1.9%. The standard deviation of the fuel economy results is approximately ±0.1608 MPG, which is small enough to be reasonably neglected in practical application.

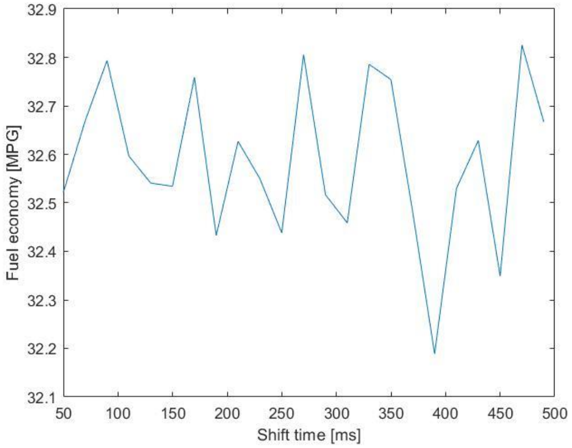


Figure 33: Fuel Economy vs Transmission Shift Time [38]

At the time of writing, the modeled hybrid supervisory controller exhibits unexpected behavior. This unexpected behavior is repeatedly observed during long drive cycles when under a sustained acceleration event. Despite the SOC being relatively high, the controller will tend to overload the engine with a high torque command and perform regenerative braking. Although this is a tradeoff between energy consumption and performance, this behavior is unfavorable for driving experience overall as it unexpectedly puts the engine under high loads. Furthermore, the energy consumption strategy in this case does not consider the future energy losses from the motor, which may as a result slightly overestimate the fuel economy results from this unique limitation.

Other assumptions not formally evaluated but inherent to the model include constant environmental conditions (no grade, no wind, etc.). Any deviations from these environmental conditions are specific testing cases that would not be included in basic architecture design and selection. Overall, an upper estimate of the validity of the results is that the true fuel economy values are ± 1.65 MPG from the modeled ones, suggesting reasonably accurate fuel economy results. While the deviation is somewhat significant, it is likely that further development and optimization of the control strategies and CAV capabilities throughout the vehicle development process will be able to offset most negative deviations from the expected modeled results presented.

7.4 VTS Performance Results

VTS performance as simulated using the vehicle model and ECMS/A-ECMS control strategy is shown in Table 7-1.

Table 7-1: Simulated VTS Performance [25]

VTS Specification	Units	Competition Target	Team VTS Target	Simulated Performance
Acceleration IVM-60mph	s	7	5.5	4.7
Acceleration 50-70mph	s	6.5	5.8	4.15
Braking 60-0mph	ft	138.4	158.2	139.72
Cargo Capacity	ft^3	Stock	Stock	Stock
Passenger Capacity	$Persons$	5	5	5
Curb Mass	kg	N/A	2100	2036.3
Starting Time	s	<=2	<2	<2
Ground Clearance	$in.$	N/A	8.89	8.89
Total Range	$mi.$	250	268.5	308.8
Fuel Economy	mpg	33.5	30.83	30.88
Emissions	g/mi	Stock	Stock	Stock
Gradeability	% @ 60mph for 20 mins	N/A	3.5	3.5

Further analysis of the simulated performance of the selected architecture reveals provides deeper insight on the benefits and drawbacks of the overall design. The heavily electrified nature of the powertrain results in aggressive acceleration characteristics. The team target accounts for a safety buffer which should address any model inaccuracies or assumptions as discussed earlier. Both simulated performance and team target values suggest the UWAFT-designed Blazer will have a longer stopping distance than the competition target of 138.4 ft. This is a known trade-off that results from the choice to utilize low rolling resistance tires, thus improving fuel economy. The stock ground clearance has been maintained to ensure overall quality in ride comfort. Furthermore, the aerodynamic benefits typically seen with the reduction of ride height did not have any significant impact on fuel economy.

As stated, this vehicle architecture was selected specifically for its potential fuel economy benefits. Although the simulated fuel economy performance currently falls short of the competition target, the designed vehicle performs well above that of market competitors. In addition, UWAFT is confident that a potential exists for further fuel economy optimization via the application of CAV technology, optimal control strategies, and parameter tuning.

PART III:

Conclusions

Chapter 8
Conclusions

The selected was chosen as the preferred architecture as it exemplifies the optimum balance between vehicle performance, integration risk minimization, and cost-of-ownership making it the best choice overall. In this cost-risk-benefit analysis, a custom weighting function was designed to capture the team's strategy to keep risk at an acceptable level and simultaneously maximize the reward. This method allowed UWAFT to make data-driven decisions throughout the design process – iterating to test new ideas. The custom ESS solution, currently under development, serves as the centerpiece and the origin in which the remainder of the vehicle's design is based. As shown throughout this thesis, component selection, sizing, architecture layout, and control strategy decisions have all been made to realize the maximization of fuel economy via heavy powertrain electrification and utilization.

To summarize, the key reasons influencing, and consequences of the final architecture selection are presented as follows in Table 8-1.

Table 8-1: Impacts of Final Architecture Selection

	Consequences Resulting from Final Architecture Selection
CAV	• Vehicle model is simple due to the simplicity of the vehicle architecture allowing for rapid development and verification of CAV controls. • The simplicity of the vehicle model allows for a lightweight model to be developed for advanced CAV controls such as optimal control for ACC, LKA, lane centering, AEB and trajectory tracking in real-time.
Controls	• The limited number of mechanical powertrain components and disconnects as well as HV components narrow down the number of modes and transitions required for optimization of the control system, limiting risk and simplifying controls development. • Modularity in the vehicle architecture allows the vehicle to drive in either engine only mode, EV only mode, or combined which reduces risk of not being able to test controls code since there is redundancy in the traction system.
Electrical	• Electrical integration risk is minimized by limiting the number of high voltage electrical components required to an absolute minimum; no DC/DC, no P0 motor, no high voltage junction box. • HV components are isolated to the rear of the vehicle which simplifies electrical routing. • OEM alternator and starter still present to allow for an engine-only mode in case a problem arises in the high voltage system.
Mechanical	• Integration risk of the ICE powertrain is substantially reduced by minimizing the number of custom parts involved. • Integration risk of the EV powertrain is largely isolated to the rear cradle. While substantial modification of the cradle is required, the mechanical challenge is largely limited to only the cradle as integration of other components were designed with simplicity and reliability in mind to balance the risk and integration effort. • EV thermal routing is isolated to the rear axle while the ICE thermal routing is isolated to the front axle, further simplifying the design.

8.1 Discussion

The intent of this thesis is to provide the reader with the requisite theoretical knowledge and practical understanding on the process of designing a HEV optimized for fuel economy. This process starts in earnest with proper analysis of the intended application, typical use cases, and target market. This information can then be used to define design requirements, objectives, and constraints ultimately leading to the formation of a vehicle design strategy. The key pillars of the vehicle design strategy followed are as follows;

> MODULARITY - The vehicles independent axle architecture allows for independent development of Internal combustion and EV powertrains ensuring vehicle downtime is kept to a minimum.
>
> SIMPLICITY – A conscious effort was made to pursue architectures of reduced complexity. The relatively simplistic nature of the final design aims to the number of failure points leading to lowered overall maintenance costs.
>
> TEST DRIVEN DEVELOPMENT – Every system in the vehicle has been designed satisfy a set of associated key requirements, undergoing iterations until it sizable to do so.

Comparative analysis of other vehicles competitive market segment in order to asses if the primary deign objective, the maximization of fuel economy, has been achieved successfully. The results of this summary are summarized in the Appendix. As shown, the designed vehicle has the best fuel economy of all market competitors evaluated, however additional opportunity exists for fuel economy improvements via the implementation of CAV technology. Table 8-2 highlights CAV technology that will be implemented in the development vehicle and their potential impacts on fuel economy (FE).

Table 8-2: CAV Features and associated FE impacts [47]

CAV Technology	Eco-Driving Impacts	Optimal EMS impacts	FE impact
Camera Systems	Localized velocity modification helps enable adaptive cruise control	Localized prediction of future velocity through sign recognition	Small FE improvements from short predictions
Radio detection and ranging (RaDAR)	Localized velocity modification fully enables adaptive cruise control	**Localized prediction of future velocity through object recognition**	Small FE improvements on the highway
Global Positioning System (GPS)	Velocity modification to coincide with speed limits along the route	Basic prediction of the full drive cycle using stop light and speed limit information	Prediction accuracy-dependent FE improvements along an entire route
Drive cycle database	Velocity modifications in historically costly sections of the drive cycle	Route length velocity predictions that improve with repeated trips	Prediction accuracy-dependent FE improvements along an entire route
Vehicle-to-Vehicle Comm. (V2V)	Opens numerous driving modifications and enables cooperative adaptive cruise control	High accuracy of future velocity prediction along a busy road	Large FE improvements along busy roads
Vehicle-to-Infrastructure Comm (V2I)	Enables velocity modifications along an entire route that coordinates with traffic signals	High accuracy of future velocity prediction near traffic lights	Large FE improvements near traffic lights
Vehicle-to-Everything Comm. (V2X)	Enables full velocity modification along an entire route while accounting for all drive cycle obstructions	High accuracy of future velocity prediction along the full route	Enables absolute optimal FE

8.2 Future Work

Although the primary design initiative has been completed, the vehicle in still very much in the early stages of development. The following sections include recommendations for future work to be completed in order to ensure continued success and innovation throughout the project.

8.2.1 Battery Pack Model Refinement

Detailed performance characteristics of the battery pack remains as one of the largest unknowns pertaining to the vehicle's design, and thus the area in which the largest improvements and overall efficiency can be made. UWAFT's current vehicle model includes a 0th order battery model. Up grading this model from DC resistance to a 1st Order RC pair Model provides improved transient voltage response to changing current. Improved transient voltage prediction is important to dynamic HEV loads profiles and have been proven to smooth engine loading and regen braking performance [48].

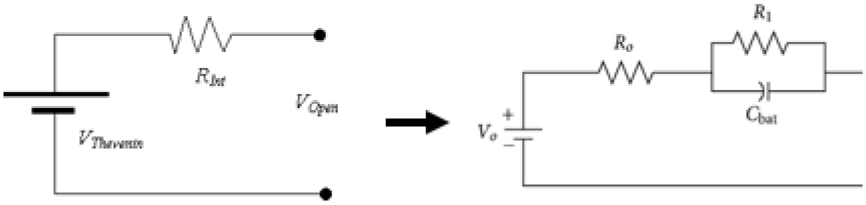


Figure 34: Proposed Model Refinement [39]

In this 1-RC model, Open Circuit Voltage (OCV) can be calculated via a SOC based look up table. UWAFT is currently conducting OCV/SOC cell testing, the result of which will be used to populate the lookup table. Preliminary results of the testing can be found in the Appendix. Hybrid Pulse Power Characterization (HPPC) test method as defined in IEC-62660 [49] [50], should also be performed in order to define R_o , R_1, and C_{batt} values at various temperatures and SOC levels. The results of one HPPC test cycle completed at 22^0C is presented in the Appendix.

8.2.2 MaaS Drive Cycle Analysis

As noted in A.C. Mersky et al. drive cycles currently used to evaluate fuel economy and overall energy consumption do not accurately reflect the typical use case and utilization for autonomous vehicles deployed in a MaaS application. Thus, an argument can be made that published fuel economy and energy consumption numbers for these vehicles are misleading. The author recommends that research team investigates the creation of a new drive cycle based on real-world driving and utilization data captured from MaaS fleet vehicles. Upon its creation, the “MaaS drive cycle” should be used to characterize and quantify energy consumption of various MaaS vehicles and provide a comparison of the equivalent energy consumption metrics provided via traditional drive cycles. Suggested vehicle candidates for data capture and analysis include: Lime electric scooters, Ridesharing vehicles, and Carsharing vehicles.

8.2.3 Design Back propagation

This thesis has presented the process taken in designing a Hybrid Electric Vehicle with considerations made specifically for its intended use case, future work could confirm the validity of the process and determine the overall success in achieving the initial objectives. This future work would take a fully conceptualized vehicle architecture and employ Model Predictive Control, Machine learning, and Artificial Intelligence techniques to deduce the application in which the vehicle would be most energy efficient.

8.2.4 CAV Innovations

Arguably the most important future work simply involves furthering the connection between Connected and Automated Vehicle technology with energy consumption. Recommendations for potential areas of research are listed below. These studies will ensure that UWAFT continues to remain at the forefront of innovation in the fields of Machine Intelligence, Artificial intelligence, Vehicle Autonomy.

Recommended areas of research:

1. Dynamic Route Planning based on energy consumption minimization
2. Driver Behavior Recognition. (Continuation of the work originally presented in [51]).
3. Future utilization prediction used to determine when appropriate times for charging.
4. Operational fleet management – Vehicle queuing.

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PART IV:

Appendix

APPENDIX A

Architecture Evaluation

A: Architecture Evaluation Table

	P4 EA				P0P4		P4(PD)							
ENGINE	2.0D	2.0E	**2.0H**	**2.5L**	1.5L	1.5L	2.5L	2.0D	2.0E	2.0H	2.5L	2.0D	2.0E	2.0H
MOTOR	AAM EDU2	AAM EDU2	**AAM EDU2**	**AAM EDU4**	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271	Phi 271
DIFF	N/A	N/A	**N/A**	**N/A**	AAM (7.97)	Audi (3.31)	AAM (7.97)	AAM (7.97)	AAM (7.97)	AAM (7.97)	Audi (3.31)	Audi (3.31)	Audi (3.31)	Audi (3.31)
ESS	HEV4	HEV4	**HEV4**	**HDS**	HDS	HDS	HDS	HDS	HDS	HDS	HDS	HDS	HDS	HDS
0 - 60	4.840298628	4.9	**4.8**	**4.7**	4.75	5.75	4.973446134	4.3	4.35	4.25	6.15	5.0832686	5.15	5.01291056
50 -70	6.05	5.4	**5.05**	**4.15**	3.7	4.5	4	4.122288684	3.6	3.95	5.05	4.7	4.1	4.55
60 - 0	139.8182823	140.045	**1.38E+02**	**1.40E+02**	1.40E+02	136.919576	1.36E+02	139.1896474	138.6063251	139.9353321	133.19113	135.4592	134.9346618	136.08
Combine	32.13051198	31.76318645	**30.8326032**	**30.88031337**	31.33600438	31.3195112	30.574917	32.25013335	32.21311397	32.3564226	30.7950581	31.184467	31.22552597	31.0927589
City	31.90251904	31.4181185	**28.78903185**	**29.40817099**	32.22263369	31.2738753	29.8303445	32.18694001	32.13942097	32.36016857	30.1269249	30.340791	30.41743699	30.4055827
City %	-0.999863743	-0.98913629	**-0.090848538**	**0.041235555**	-0.990400118	-0.9995999	-0.027714533	-0.997404399	-0.955177512	-0.957471186	-1.0080494	-0.9890403	-0.97490285	-0.9719814
HighWay	32.41363445	32.19536982	**33.76172587**	**32.89279909**	30.31645188	31.3754696	31.53701538	32.32770743	32.30364343	32.35184537	31.6530313	32.281587	32.27345583	31.9760207
HighWay %	-0.100782844	-0.10542341	**0.130722599**	**0.195693461**	-0.289436462	-0.40908175	-0.170117416	-0.452712336	-0.457910515	-0.430151271	-0.4495424	-0.4483403	-0.48192453	-0.4347268
HC	0.209017011	0.208938002	**0.130340795**	**0.245918647**	0.437278033	0.46127312	0.434661681	0.230382396	0.219545982	0.20441737	0.49773321	0.3066615	0.306173636	0.29205773
CO	0.65922344	0.606847615	**0.838208394**	**1.934282411**	8.061451645	9.03427539	2.171577236	0.604797563	0.510655281	0.508481453	3.97845516	2.7806288	2.780930385	2.81572437
Nox	0	0	**0**	**0.088510081**	0	0	0.11814967	0	0	0	0.10814091	0	0	0
Range	321.3051198	317.6318645	**308.326032**	**308.8031337**	313.3600438	313.195112	305.74917	322.5013335	322.1311397	323.564226	307.950581	311.84467	312.2552597	310.927589
	878.0449982	867.3469388	**885.4166667**	**904.2553191**	894.7368421	739.130435	854.5382588	988.372093	977.0114943	1000	691.056911	836.07622	825.2427184	847.810858
	595.0413223	666.6666667	**712.8712871**	**867.4698795**	972.972973	800	900	873.3012838	1000	911.3924051	712.871287	765.95745	878.0487805	791.208791
	952.6016742	951.0595152	**968.0759053**	**953.2753992**	951.0595152	972.769079	980.2400687	956.9039961	960.9311098	951.8048642	1000	983.25646	987.0786945	978.770795
	993.0180593	981.6655828	**952.9051952**	**954.3797145**	968.463194	967.953458	944.941206	996.7150491	995.5709371	1000	951.744835	963.77983	965.0487741	960.945507
	623.5894135	623.8252211	**1000**	**530.0159089**	298.073046	282.567504	299.8672325	565.758484	593.6833554	637.6209387	261.868794	425.03145	425.7087485	446.284354
	771.3340001	837.9063211	**606.6289197**	**262.8786003**	63.07566865	56.2835901	234.1530591	840.7465307	995.7430608	1000	127.808768	182.86563	182.8458042	180.586373
	1000	1000	1000	**0**	1000	1000	0	1000	1000	1000	0	1000	1000	1000
	993.0180593	981.6655828	**952.9051952**	**954.3797145**	968.463194	967.953458	944.941206	996.7150491	995.5709371	1000	951.744835	963.77983	965.0487741	960.945507
	850.8309409	863.7669785	**884.8503962**	**678.331817**	764.6055541	723.332191	644.8351289	902.3140607	939.8138618	937.602276	587.136929	765.09336	778.6277868	770.819023
VTS	850.8309409	863.7669785	**884.8503962**	**678.331817**	764.6055541	723.332191	644.8351289	902.3140607	939.8138618	937.602276	587.136929	765.09336	778.6277868	770.819023
COST	872.7023206	872.7023206	**872.7023206**	**1000**	877.0689512	877.068951	1000	722.9892706	722.9892706	722.9892706	1000	722.98927	722.9892706	722.989271
	400	400	700	800	700	700	800	400	400	700	800	400	400	700
	677.9661017	677.9661017	677.9661017	1000	427.9661017	427.966102	872.8813559	872.8813559	872.8813559	872.8813559	872.881356	872.88136	872.8813559	872.881356
RISK	1077.966102	1077.966102	**1377.966102**	**1800**	1127.966102	1127.9661	1672.881356	1272.881356	1272.881356	1572.881356	1672.88136	1272.8814	1272.881356	1572.88136
FINAL EVALUATION PTS	2904.131254	2917.067291	**3388.150709**	**3878.331817**	2895.089182	2853.81582	3654.157163	3173.13073	3210.630531	3658.418945	3596.45896	3035.91	3049.444456	3491.63569

APPENDIX B

Preliminary Cell Testing

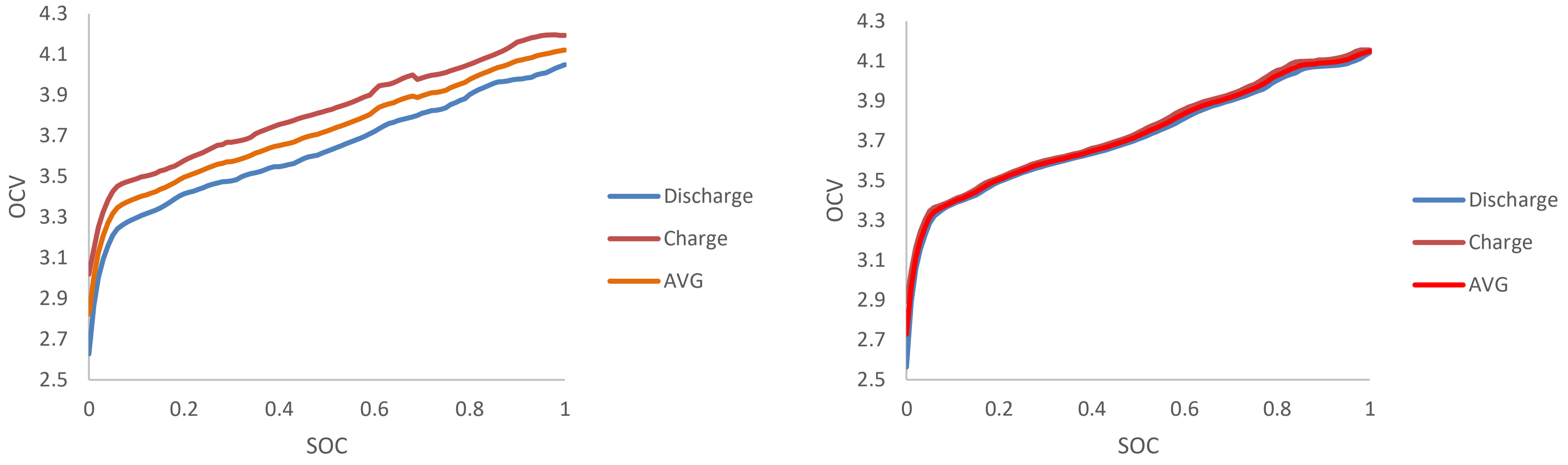


Figure 35: Preliminary SOC-OCV Test results (Cell 1- left | Cell 2 - right

Table A-1: Preliminary 1-RC Model Cell Parameters

SOC	R0	R1	C1
100	0.**3388**	0.0955	2.5403e+03
90	0.**3233**	**0.0028**	1.4000e+04
80	**0.2902**	0.0038	1.3322e+04
70	0.**2758**	0.0037	1.4406e+04
60	0.**2732**	0.0029	1.4580e+04
50	0.2719	0.0030	1.4062e+04
40	0.2638	0.0029	1.3504e+04
30	0.2668	0.0039	1.2480e+04
20	0.2723	0.0042	1.1393e+04
10	0.3063	0.0056	9.6862e+03

APPENDIX C

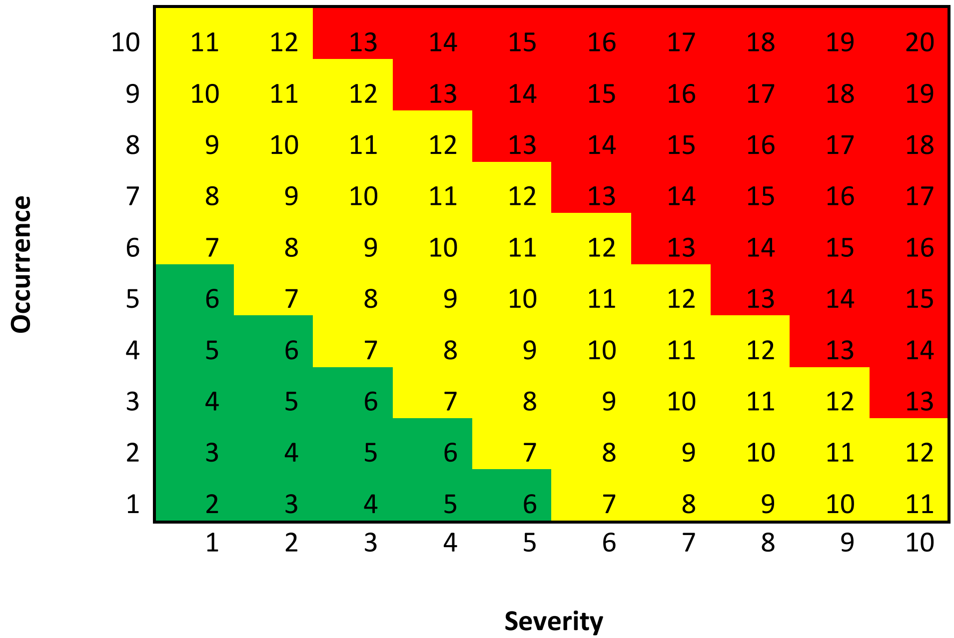
Competitive Segment Comparison

Table A-2:Competitive Segment Comparison

VTS Specification	Units	RAV4 AWD	KIA Sorento	BMW X1	Santa Fe AWD	Nissan Rogue	Audi Tiguan	UWAFT Blazer
Acceleration IVM-60mph	s	8.30	9.9	6.6	7.8	9.1	8.2	5.5
Acceleration 50-70mph	s	6.0	8.5	4.8	5.2	6.1	6.0	5.8
Braking 60-0mph	ft	143.0	116.0	N/A	125.0	137.0	123.0	158.2
Cargo Capacity	ft^3	38.3	38.8	18.0	35.0	39.3	37.6	30.5
Passenger Capacity	$Persons$	5	7	5	5	5	5	5
Curb Mass	kg	1610	1942.3	1660	1790	1550	1713.0	2100
Ground Clearance	$in.$	6.13	7.28	7.20	7.28	7.38	7.87	8.89
Total Range	$mi.$	420.5	479.4	462.65	479.40	413.25	397.5	308.8
Fuel Economy	mpg	28.8	25.0	25.0	25.0	27	24	30.88

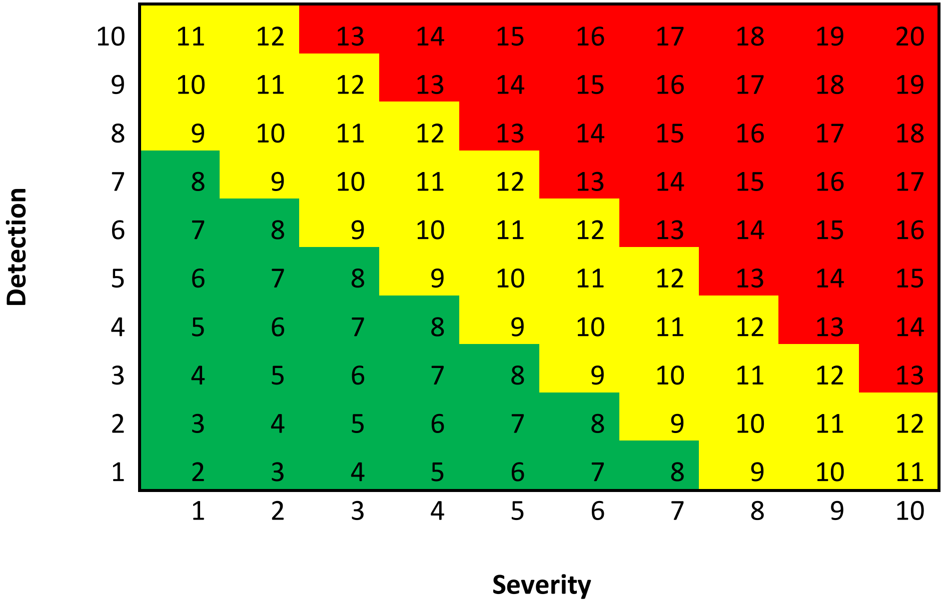
APPENDIX D

Risk Evaluation Matrix



Occurrence	1	2	3	4	5	6	7	8	9	10
10	11	12	13	14	15	16	17	18	19	20
9	10	11	12	13	14	15	16	17	18	19
8	9	10	11	12	13	14	15	16	17	18
7	8	9	10	11	12	13	14	15	16	17
6	7	8	9	10	11	12	13	14	15	16
5	6	7	8	9	10	11	12	13	14	15
4	5	6	7	8	9	10	11	12	13	14
3	4	5	6	7	8	9	10	11	12	13
2	3	4	5	6	7	8	9	10	11	12
1	2	3	4	5	6	7	8	9	10	11

Severity



Detection	1	2	3	4	5	6	7	8	9	10
10	11	12	13	14	15	16	17	18	19	20
9	10	11	12	13	14	15	16	17	18	19
8	9	10	11	12	13	14	15	16	17	18
7	8	9	10	11	12	13	14	15	16	17
6	7	8	9	10	11	12	13	14	15	16
5	6	7	8	9	10	11	12	13	14	15
4	5	6	7	8	9	10	11	12	13	14
3	4	5	6	7	8	9	10	11	12	13
2	3	4	5	6	7	8	9	10	11	12
1	2	3	4	5	6	7	8	9	10	11

Severity

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Controls RA	1	Motor/engine failure recovery.	As the electric drivetrain is detached from the ICE, if one component fails (or battery is depleted in the case of motor) the entire controls strategy must account for this change to the new type of drivetrain.	10	1	10	21	🟨 11	🟨 11	Identify signs of failure before occurrence (ie motor/engine not meeting control requests, calculations based on active SOC/SOH of battery... etc). Attempt to make transition before failure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor/engine fails or usable battery SOC reaches 0.
	2	Signal Unit Conversion	In the model/controller, if the units of signals are not matching with each other, it would cause unrealistic commands to be sent. They do not meet what is actually needed. This will causes command from controller to be off further more and accumulate overtime. Eventually confusion would happen and control unit would not be able to solve the problem.	8	3	8	19	🟨 11	🟨 11	Label all signals in the model to clarify their units and validate them after every few updates.	Switch to stock vehicle operation mode? Using the simplest controller with just engine.	Controller unable to solve the signals or data seems to be off from normal operating range.
	3	Vehicle not starting due to controller	Seriously impedes vehicle development and testing	6	6	0	12	🟨 12	🟩 6	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Continuous Integration regression Testing should flag and prevent this risks from materializing	Revert to Previously Known working Controls Code	Upon Failure
	4	Tuning of controls constants.	Incorrect tuning of P, I and D constants (and other aspects of the controllers) will result in non optimal performance and/or energy consumption, depending on the scenario.	5	10	3	18	🟥 15	🟥 13	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Develop/use algorithm to define optimal constants.	Utilize controller during trip and note improvements to be made.	Performance and/or energy consumption is significantly worse than predicted.
	5	SOC management and advanced controls for start/stop feature cannot be completed in time for Y3 competition	degradation of fuel economy, missed FE target, loss of critical consumer feature,	6	7	0	13	🟥 13	🟩 7	Start working on these controls algorithms at the end of Y1	N/A	N/A
	6	Inaccurate simulation data.	Not meeting VTS, poorer performance and efficiency than anticipated. Physical vehicle does not meet controls expectations.	8	8	9	25	🟥 16	🟥 17	Continuous development in SIL and HIL environments, constant communication amoungst team members and industry experts.	Recognize potential for inaccuracy, make judgments based on comparisons between models (ie compare to stock Blazer)	Contingency plan should be always in mind.
	7	Usable SOC reaches 0 unexpectedly/ battery ESS fails to communicate with controller.	This case is similar to the above case where the motor fails.	10	1	7	18	🟨 11	🟩 8	Perform extensive testing on ESS prior to integration, test on motor outside of vehicle, read voltage and current information from controller and compare to physical measurements. Establish calibration procedure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor stops providing power.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
	1	The HV cable is damaged and exposed	Exposed cable contacts with chassis Destroy other components Injure/kill person Unsafe discharge of HV bus, damaging components Exposed cable contacts directly with person, injuring/killing them Exposed cable must be replaced/repaired	10	4	3	17	🟥 14	🟩 7	Regular inspection of HV cables to ensure they are intact properly insulated and intact.	Replace or repair HV cable.	Cable is visibly exposed Unusually high battery discharge current detected by MABx With HV disconnected (MSD removed), measure continuity/resistance between HV line and chassis
	2	The HV cable is mechanically bent/kinked by another part to an unsafe angle	Increases resistance in the wire Heats up wire Draws more power from the battery	9	4	3	16	🟥 13	🟩 7	Regular inspection of HV cables to ensure they remain with the required bend radius (~3-4in)	Replace or repair HV cable.	Cable is seen to be bent There is higher than normal power draw from the HDS battery Components/frame around the part are hot

	3	The HV battery is depleted below safe SoC levels	Battery cannot be recharged If it is recharged, battery meltdown could occur	6	2	1	9	🟨 8	🟩 3	Implement controls safety system to check battery levels	Replace battery	Battery SoC levels are reported by BMS over CAN to be below safe levels
	4	The alternator for charging the 12V system fails	All vehicle systems can no longer function due to the 12V battery being quickly depleted (without charging)	7	1	5	13	🟨 8	🟩 6	Verify the output shaft speed from the engine. Make sure alternators motor speed can operate at that level.	Replace alternator (Relatively easy)	12V battery SOC, reported by BMS over CAN, is dropping too quickly, indicating it is not being charged
	5	The HV bus cable(s), connecting to the P4 inverter and to the P4 motor, are broken	The P4 inverter/motor will not be able to produce torque / provide regen If there is no regen the battery will no be able to be recharged	6	4	1	11	🟨 10	🟩 5	Have some control system to monitor the voltage/current levels. Properly secure the cables and/or ensure they are protected.	Replace HV cable(s)	Motor is not running, or improperly running. There is no regen going to the battery.
	6	HV bus routing from the top of the Malibu battery is damaged	The HV connections on the malibu battery are on the top of the battery pack , this creates more exposure for the cables to be damaged	6	4	1	11	🟨 10	🟩 5	Create some protective covering to prevent the HV cables from being damaged.	Replace HV cables, add better protection	None of the HV components are receiving power.
	7	AMM motor connection to HV (Have to get info on AAM motor HV connection	N/A							N/A	N/A	N/A

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Mechanical RA	1	INTEGRATION:	CONFIGURATION 1:	5	7	7	19	🟨 12	🟥 14	Preform many iterations of FEA while the design process is occurring	Do a different architecture	EDU2 mounting and rear cradle modification doesn't meet requirements. Or EDU2 system fails.
		CONFIGURATION 1:	Changing mounting design. Potentially not using eAxle solution at all									
		stock half-shaft is not aligned with eAxle in order to prevent significant interference with the rear cradle										
		the custom half-shaft will rest at an angle to the eAxle- causes inefficiencies (power losses)	CONFIGURATION 2:									
			Electrification of driveline not completed within schedule									
		Minimal interference with the rear cradle:										
		RISK (low):										
		complications involving the custom half-shafts: feasibility, length										
		mounting										
		CONFIGURATION 2:										
		eAxle perfectly aligns with half-shaft → pushed deeper into the rear cradle and shifted forwards. This prevents the inefficiencies associated with an angled half-shaft position										
		significant interference with the rear cradle										
		significant rear cradle modifications required: cradle will need to be cut, shifted upwards and re-welded										
		RISKS (high):										
		extensive manpower required to preform rear cradle modifications										
		waivers required										
		need members capable of welding										
	2	EDU4 will require custom rear half shafts: manufacturing challenge (finding a manufacturer)	Cannot find a manufacturer.	7	7	0	14	🟥 14	🟩 7	FEA to determine the torque output/strain on each half shaft.	Have volunteers researching custom half shaft manufacturing.	Immediately
		Design considerations to keep the torque balanced between shafts and prevent torque steering or from breaking.	Broken half shaft could damage the wheels, rear suspension assembly and EDU4 unit.							Design: One shaft is required to be longer than the other, therefore other shaft must be larger in diameter in order for both shafts to have the same inertia.		
			Torque steering affects drivability.									
		Total					236					

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Controls RA	1	Motor/engine failure recovery.	As the electric drivetrain is detached from the ICE, if one component fails (or battery is depleted in the case of motor) the entire controls strategy must account for this change to the new type of drivetrain.	10	1	10	21	🟨 11	🟨 11	Identify signs of failure before occurrence (ie motor/engine not meeting control requests, calculations based on active SOC/SOH of battery... etc). Attempt to make transition before failure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor/engine fails or usable battery SOC reaches 0.
	2	Signal Unit Conversion	In the model/controller, if the units of signals are not matching with each other, it would cause unrealistic commands to be sent. They do not meet what is actually needed. This will causes command from controller to be off further more and accumulate overtime. Eventually confusion would happen and control unit would not be able to solve the problem.	8	3	8	19	🟨 11	🟨 11	Label all signals in the model to clarify their units and validate them after every few updates.	Switch to stock vehicle operation mode? Using the simplest controller with just engine.	Controller unable to solve the signals or data seems to be off from normal operating range.
	3	Vehicle not starting due to controller	Seriously impedes vehicle development and testing	6	6	0	12	🟨 12	🟩 6	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Continuous Integration regression Testing should flag and prevent this risks from materializing	Revert to Previously Known working Controls Code	Upon Failure
	4	Tuning of controls constants.	Incorrect tuning of P, I and D constants (and other aspects of the controllers) will result in non optimal performance and/or energy consumption, depending on the scenario.	5	10	3	18	🟥 15	🟥 13	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Develop/use algorithm to define optimal constants.	Utilize controller during trip and note improvements to be made.	Performance and/or energy consumption is significantly worse than predicted.
	5	SOC management and advanced controls for start/stop feature cannot be completed in time for Y3 competition	degradation of fuel economy, missed FE target, loss of critical consumer feature,	6	7	0	13	🟥 13	🟩 7	Start working on these controls algorithms at the end of Y1	N/A	N/A
	6	Inaccurate simulation data.	Not meeting VTS, poorer performance and efficiency than anticipated. Physical vehicle does not meet controls expectations.	8	8	9	25	🟥 16	🟥 17	Continuous development in SIL and HIL environments, constant communication amoungst team members and industry experts.	Recognize potential for inaccuracy, make judgments based on comparisons between models (ie compare to stock Blazer)	Contingency plan should be always in mind.
	7	Usable SOC reaches 0 unexpectedly/ battery ESS fails to communicate with controller.	This case is similar to the above case where the motor fails.	10	1	7	18	🟨 11	🟩 8	Perform extensive testing on ESS prior to integration, test on motor outside of vehicle, read voltage and current information from controller and compare to physical measurements. Establish calibration procedure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor stops providing power.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Electrical RA	1	60kw motor may pull too much current from 52kW battery	To compensate for the massive current draw, the batteries voltage will drop which will damage the battery and reduce life expectancy	5	5	1	11	🟨 10	🟩 6	Implement controls system to monitor current draws, this can hopefully prevent too much current draw.	Replace battery/module/cells, whichever is best. Implement system to prevent this from occurring again.	The power draw from the battery is much higher than safe levels.
	2	The HV cable is damaged and exposed	Exposed cable contacts with chassis Destroy other components Injure/kill person Unsafe discharge of HV bus, damaging components Exposed cable contacts directly with person, injuring/killing them Exposed cable must be replaced/repaired	10	4	3	17	🟥 14	🟩 7	Regular inspection of HV cables to ensure they are intact properly insulated and intact.	Replace or repair HV cable.	Cable is visibly exposed Unusually high battery discharge current detected by MABx With HV disconnected (MSD removed), measure continuity/resistance between HV line and chassis
	3	The HV cable is mechanically bent/kinked by another part to an unsafe angle	Increases resistance in the wire Heats up wire Draws more power from the battery	9	4	3	16	🟥 13	🟩 7	Regular inspection of HV cables to ensure they remain with the required bend radius (~3-4in)	Replace or repair HV cable.	Cable is seen to be bent There is higher than normal power draw from the HDS battery Components/frame around the part are hot
	4	The HV battery is depleted below safe SoC levels	Battery cannot be recharged If it is recharged, battery meltdown could occur	6	2	1	9	🟨 8	🟩 3	Implement controls safety system to check battery levels	Replace battery	Battery SoC levels are reported by BMS over CAN to be below safe levels

	5	The alternator for charging the 12V system fails	All vehicle systems can no longer function due to the 12V battery being quickly depleted (without charging)	7	1	5	13	8	6	Verify the output shaft speed from the engine. Make sure alternators motor speed can operate at that level.	Replace alternator (Relatively easy)	12V battery SOC, reported by BMS over CAN, is dropping too quickly, indicating it is not being charged
	6	The HV bus cable(s), connecting to the P4 inverter and to the P4 motor, are broken	The P4 inverter/motor will not be able to produce torque / provide regen	6	4	1	11	10	5	Have some control system to monitor the voltage/current levels. Properly secure the cables and/or ensure they are protected.	Replace HV cable(s)	Motor is not running, or improperly running. There is no regen going to the battery.
			If there is no regen the battery will no be able to be recharged									
	7	HV bus routing from the top of the Malibu battery is damaged	The HV connections on the malibu battery are on the top of the battery pack , this creates more exposure for the cables to be damaged	6	4	1	11	10	5	Create some protective covering to prevent the HV cables from being damaged.	Replace HV cables, add better protection	None of the HV components are receiving power.
	8	AMM motor connection to HV (Have to get info on AAM motor HV connection	N/A							N/A	N/A	N/A

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Mechanical RA	1	INTEGRATION:	CONFIGURATION 1:	5	7	7	19	12	14	Preform many iterations of FEA while the design process is occurring	Do a different architecture	EDU2 mounting and rear cradle modification doesn't meet requirements. Or EDU2 system fails.
		CONFIGURATION 1:	Changing mounting design. Potentially not using eAxle solution at all									
		stock half-shaft is not aligned with eAxle in order to prevent significant interference with the rear cradle										
		the custom half-shaft will rest at an angle to the eAxle- causes inefficiencies (power losses)	CONFIGURATION 2:									
			Electrification of driveline not completed within schedule									
		Minimal interference with the rear cradle:										
		RISK (low):										
		complications involving the custom half-shafts: feasibility, length										
		mounting										
		CONFIGURATION 2:										
		eAxle perfectly aligns with half-shaft → pushed deeper into the rear cradle and shifted forwards. This prevents the inefficiencies associated with an angled half-shaft position										
		significant interference with the rear cradle										
		significant rear cradle modifications required: cradle will need to be cut, shifted upwards and re-welded										
		RISKS (high):										
		extensive manpower required to preform rear cradle modifications										
		waivers required										
		need members capable of welding										
	2	Fitting and Mounting either the 1.5 or 2.0 L engines. Mount failure to hold engine or create enough dampening.	Engine gets displaced damaging the drive line. The vehicle has bad vibrations caused by the engine displacement	10	7	5	22	17	12	Perform proper FEA analysis for many different test cases. Also pay close attention to material selection for mount and rubber bushing.	Jump off E5	Engine falls out and drags across the fucking road.
	3	Front half-shaft from transmission to the wheels that we plan on getting from another vehicle with the same powercube could break or may not fit.	One of the front wheels would loose torque output, Shaft breaking may damage suspension assembly and other components around it. If shaft does not fit, we would need to look at other options.	7	7	5	19	14	12	Proper FEA analysis has to be conducted and splines have to be properly manufactured. Shaft must also be weight balanced with a CV joint on each end. May need to investigate coupling between half-shaft and trans.	Look into custom half shaft solutions.	Vibrations caused through the shaft, shaft breaks, or doesn't fit.
											Waiting to receive half shaft cad from Gaffney.	
	4	EDU2 will require custom rear half shafts: manufacturing challenge (finding a manufacturer)	Cannot find a manufacturer.	7	7	0	14	14	7	FEA to determine the torque output/strain on each half shaft.	Have volunteers researching custom half shaft manufacturing.	Immediately
		Design considerations to keep the torque balanced between shafts and prevent torque steering or from breaking.	Broken half shaft could damage the wheels, rear suspension assembly and EDU2 unit.							Design: One shaft is required to be longer than the other, therefore other shaft must be larger in diameter in order for both shafts to have the same inertia.		
			Torque steering affects drivability.									
	5	No replacement if this unit breaks!!	No hybrid vehicle. Incur RAD and RAI penalties due to a change in major propulsion system component	10	7	7	24	17	14	Communication with AAM every step of the integration and control strategy development process.	Preemptively investigate AAM RMA repair process. Identify potential back up traction motor solutions	Prior to requesting donated AAM EDU2
		Total					312					

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ.	Det.	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Controls RA	1	Main starter system/P0 motor fails	Car is unable to start, P0 motor is out of sync with engine due to friction loss, damage to components.	9	8	6	23	🟥 17	🟥 14	Requires backup starter system that uses only the ICE, detection method by the motor controller and/or ecm.	Omit P0.	P0 fails/P0 rpm does not match engine rpm.
	2	Motor/engine failure recovery.	As the electric drivetrain is detached from the ICE, if one component fails (or battery is depleted in the case of motor) the entire controls strategy must account for this change to the new type of drivetrain.	10	1	10	21	🟨 11	🟨 11	Identify signs of failure before occurrence (ie motor/engine not meeting control requests, calculations based on active SOC/SOH of battery... etc). Attempt to make transition before failure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor/engine fails or usable battery SOC reaches 0.
	3	Charge sustain mode complexity	Without correct implementation of logic, vehicle mode will not meet driver's expectations.	4	8	10	22	🟨 12	🟥 18	Energy flow measurements need to be constantly taken into account between engine and both motors to determine the best method of maintaining SOC.	Alert driver, simply cycle between engine-only and AWD mode to keep SOC within reasonable range.	Vehicle recognizes it in charge sustain mode but fails to maintain SOC.
	4	Tuning of controls constants.	Incorrect tuning of P, I and D constants (and other aspects of the controllers) will result in non optimal performance and/or energy consumption, depending on the scenario.	5	10	3	18	🟥 15	🟥 13	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Develop/use algorithm to define optimal constants.	Utilize controller during trip and note improvements to be made.	Performance and/or energy consumption is significantly worse than predicted.
	5	SOC management and advanced controls for start/stop feature cannot be completed in time for Y3 competition	degradation of fuel economy, missed FE target, loss of critical consumer feature,	6	7	0	13	🟥 13	🟩 7	Start working on these controls algorithms at the end of Y1	N/A	N/A
	6	Inaccurate simulation data.	Not meeting VTS, poorer performance and efficiency than anticipated. Physical vehicle does not meet controls expectations.	8	8	9	25	🟥 16	🟥 17	Continuous development in SIL and HIL environments, constant communication amoungst team members and industry experts.	Recognize potential for inaccuracy, make judgments based on comparisons between models (ie compare to stock Blazer)	Contingency plan should be always in mind.
	7	Usable SOC reaches 0 unexpectedly/ battery ESS fails to communicate with controller.	This case is similar to the above case where the motor fails.	10	1	7	18	🟨 11	🟩 8	Perform extensive testing on ESS prior to integration, test on motor outside of vehicle, read voltage and current information from controller and compare to physical measurements. Establish calibration procedure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor stops providing power.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ.	Det.	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Electrical RA	1	The HV cable is damaged and exposed	Exposed cable contacts with chassis Destroy other components Injure/kill person Unsafe discharge of HV bus, damaging components Exposed cable contacts directly with person, injuring/killing them Exposed cable must be replaced/repaired	10	5	3	18	🟥 15	🟩 8	Regular inspection of HV cables to ensure they are intact properly insulated and intact.	Replace or repair HV cable.	Cable is visibly exposed Unusually high battery discharge current detected by MABx With HV disconnected (MSD removed), measure continuity/resistance between HV line and chassis
	2	The HV cable is mechanically bent/kinked by another part to an unsafe angle	Increases resistance in the wire Heats up wire Draws more power from the battery	9	4	3	16	🟥 13	🟩 7	Regular inspection of HV cables to ensure they remain with the required bend radius (~3-4in)	Replace or repair HV cable.	Cable is seen to be bent There is higher than normal power draw from the HDS battery Components/frame around the part are hot
	3	The HV battery is depleted below safe SoC levels	Battery cannot be recharged If it is recharged, battery meltdown could occur	7	2	1	10	🟨 9	🟩 3	Implement controls safety system to check battery levels	Enter Engine Charge Mode. Replace battery under severe circumstances.	Battery SoC levels are reported by BMS over CAN to be below safe levels

	4	P0 motor fails	This eliminate one source of power to recharge the battery, overall the system can continue to function but has to rely on P4 regen	5	4	0	9	9	4	Monitor the condition of the motor, regulation its rotational speed and ensure it does not exceed its max rpm	Replace Motor	Motor is not running or motor is overheating.
	5	DC/DC converter fails	This would prevent the LV battery from being recharged, if the battery can't be recharge the vehicle cant be recharged	7	4	5	16	11	9	Have controller check SoC for the LV battery	Replace DC/DC converter, or somehow connect alternator to LV Battery	Battery SoC levels are reported by BMS over CAN to be insufficient
	6	Wires running through the underbelly fail	Wires going through the underbelly have more exposure to external conditions, thus allowing more potential for failure	6	5	2	13	11	7	Create proper shielding for HV wires	Replace HV wires, or create better shielding	HV components such as the P0 are not receiving power
	7	P4 Motor is broken	This would cause a subsystem failure because the rear power-train could not run	6	4	0	10	10	4	Monitor the condition of the motor, regulation its rotational speed and ensure it does not exceed its max rpm. Implement safety controls system	Replace Motor, add further safety checks	Motor appears to be overheating, working inefficiently
	8	HV bus routing from the side of the HDS battery is damaged	The HV connections on the malibu battery are on the top of the battery pack , this creates more exposure for the cables to be damaged	7	4	0	11	11	4	Create some protective covering to prevent the HV cables from being damaged.	Replace HV cables, add better protection	None of the HV components are receiving power.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ.	Det.	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Mechanical RA	1	Integration of P0 - Re-tensioning the belt system Needing correct pulley size to match serpentine belt width	-Belt system breaks, no P0 regen, no low voltage regen using engine. -Many man hours spent figuring out belt tensioning system	7	6	7	20	13	13	Research into belt tensioning.	If process is determined to be infeasible, abandon P0 plan	Belt system is deemed too time consuming and costly
	2	Need to find new RDM and planetary gearbox.	Potential gear ratios not feasible for electric motor. Gearbox cannot be designed/manufactured in time by Pulse	7	7	5	19	14	12	Magna/Audi Differential- can buy unit off the shelf but will have no tech support from magna for integration. Can get tech support from MVSL. AAM Differential- 2-Speed differential. Very possible to receive control and mechanical support Pulse Planetary Gearbox- until we receive written confirmation from Pulse, proceed assuming Gearbox will not be feasible	Use stock RDM as an open differential.	No option deemed feasible/available.
	3	Custom half shafts will be required for the rear axle (differential to wheel shafts). This shaft may not be able to handle the torque output from the motor after the huge gear ratio	Shearing the half-shafts	10	7	0	17	17	7	When we reach the step of looking for a manufacturer to make these shafts for us, clearly communicate the technical specs required and feasibility	Team fabricates half-shafts in house (modification of production vehicle half-shafts)	Upon Failure
	4	Mounting the RDM to the rear cradle may require modifications to the rear cradle. Need to meet FEA requirements	May need to redesign the mounting of RDM.	5	6	6	17	11	12	Use FEA on multiple iterations of mount design.	N/A	N/A
	5	Fitting and Mounting either the 1.5 or 2.0 L engines. Mount failure to hold engine or create enough dampening.	Engine gets displaced damaging the drive line. The vehicle has bad vibrations caused by the engine	10	7	5	22	17	12	Perform proper FEA analysis for many different test cases. Also pay close attention to material selection for mount and rubber bushing. Ensure any in house fabrication is done correctly. Seek advice from driveline experts (AAM)	Re-design Engine Mounts and other driveline mounting	Upon noticing that original mounts are not sufficient.
	6	Custom front half-shaft from transmission to the wheels could break.	One of the front wheels would loose torque output, Shaft breaking may damage suspension assembly and other components around it.	7	7	5	19	14	12	Proper FEA analysis has to be conducted and splines have to be properly manufactured. Shaft must also be weight balanced with a CV joint on each end.	Team fabricates half-shafts in house (modification of production vehicle half-shafts)	Upon Failure
	7	Coolant Pump Overload	Insufficient cooling of EV system. Heavy load on coolant pump due to head losses (additional coolant lines/radiators/inverters/motors) could lead to a reduction in coolant flow rate.	4	5	5	14	9	10	Design with a safety margin	Source new coolant pump capable of meeting system load requirements	Upon noticing inadequate cooling of EV system components
		Total					371					

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Controls RA	1	Optimizing motor speed requests.	Not taking into account subtle differences in the distinct motors will mean one (inevitably) will perform worse and draw energy from the other as they both attempt to reach certain speeds.	5	10	8	23	🟥 15	🟥 18	Testing must be done on physical motors, as performance differences will require tuning of the controls. The motor that performs worse will need to be accounted for when requesting speeds or when maintaining a constant speed.	There should be a method in place to regen some of the energy lost from one motor when the two don't match up.	Motor speeds are not equal.
	2	Motor/engine failure recovery.	As the electric drivetrain is detached from the ICE, if one component fails (or battery is depleted in the case of motor) the entire controls strategy must account for this change to the new type of drivetrain.	10	1	8	19	🟨 11	🟨 9	Identify signs of failure before occurrence (ie motor/engine not meeting control requests, calculations based on active SOC/SOH of battery... etc). Attempt to make transition before failure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor/engine fails
	3	Usable SOC reaches 0 unexpectedly/ battery ESS fails to communicate with controller.	This case is similar to the above case where the motor fails.	10	1	7	18	🟨 11	🟩 8	Perform extensive testing on ESS prior to integration, test on motor outside of vehicle, read voltage and current information from controller and compare to physical measurements. Establish calibration procedure.	Initiate transition from AWD to FWD/RWD (depending on situation). Perform testing to ensure transition is secure at all speeds, environmental conditions and during turns.	Motor stops providing power.
	4	Tuning of controls constants.	Incorrect tuning of P, I and D constants (and other aspects of the controllers) will result in non optimal performance and/or energy consumption, depending on the scenario.	5	10	3	18	🟥 15	🟥 13	Sufficient testing in SIL and HIL environments prior to implementation in physical vehicle. Develop/use algorithm to define optimal constants.	Utilize controller during trip and note improvements to be made.	Performance and/or energy consumption is significantly worse than predicted.
	5	SOC management and advanced controls for start/stop feature cannot be completed in time for Y3 competition	degradation of fuel economy, missed FE target, loss of critical consumer feature,	6	7	0	13	🟥 13	🟩 7	Start working on these controls algorithms at the end of Y1	N/A	N/A
	6	Inaccurate simulation data.	Not meeting VTS, poorer performance and efficiency than anticipated. Physical vehicle does not meet controls expectations.	8	8	9	25	🟥 16	🟥 17	Continuous development in SIL and HIL environments, constant communication amoungst team members and industry experts.	Recognize potential for inaccuracy, make judgments based on comparisons between models (ie compare to stock Blazer)	Contingency plan should be always in mind.
	7	Motor unable to be controlled under normal driving conditions, oscillations in vehicle speed, torque commands not being met, etc.	Any issues with one motor need solutions implemented on the other as well. Consequently, a larger percentage of the powertrain is affected while these solutions are in development, impeding on the progress of the team.	8	5	5	18	🟥 13	🟨 10	Extensive testing in HIL environment, validation of controls strategies before implementation, research of motor characteristics.	Modify existing logic and change goals to meet realistic time and effort estimates.	Controller and theoretical data not meeting physical data, issues mainly in full-EV mode.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Electrical RA	1	The HV cable is damaged and exposed	Exposed cable contacts with chassis Destroy other components Injure/kill person Unsafe discharge of HV bus, damaging components Exposed cable contacts directly with person, injuring/killing them Exposed cable must be replaced/repaired	10	4	3	17	🟥 14	🟩 7	Regular inspection of HV cables to ensure they are intact properly insulated and intact.	Replace or repair HV cable.	Cable is visibly exposed Unusually high battery discharge current detected by MABx With HV disconnected (MSD removed), measure continuity/resistance between HV line and chassis
	2	The HV cable is mechanically bent/kinked by another part to an unsafe angle	Increases resistance in the wire Heats up wire Draws more power from the battery	9	4	3	16	🟥 13	🟩 7	Regular inspection of HV cables to ensure they remain with the required bend radius (~3-4in)	Replace or repair HV cable.	Cable is seen to be bent There is higher than normal power draw from the HDS battery Components/frame around the part are hot
	3	The HV battery is depleted below safe SoC levels	Battery cannot be recharged If it is recharged, battery meltdown could occur	6	2	1	9	🟨 8	🟩 3	Implement controls safety system to check battery levels	Replace battery	Battery SoC levels are reported by BMS over CAN to be below safe levels
	4	Exposed 3-Phase HV Connectors on EMRAX Motors	Exposed connection carrying a lot of energy → high likelihood of accidental touching/arching	10	4	0	14	🟥 14	🟩 4	Enclose the connector, be sure to connect the HV to power last	3D print a cap	You should be able to see exposed metal wrapped around the HV terminal

	5	Both HV cables to either 100 kW motor are damaged	If both cables are damaged/not connected rear motors will not drive and entire power/torque will be coming from the front engine	2	1	3	6	3	4	Ensure that physical wiring follows harness, no major tight turns/kinks	Rewire cable	Power output from rear drive will dip significantly.
	6	Cooling of EMRAX 228	If the allotted 120 degrees C (or -40 C) are passed; motor will shut down and ensure damage to bearing	8	6	2	16	14	8	Use proper cooling system (coolant pipes spec'd by EMRAX	Hope warranty is still good and pay for express shipping	Motor will fall apart and experience a large dip in power
	7	Motor are damaged due to foreign objects	Motor will possibly stop working and may not fall under warranty	10	7	2	19	17	9	When assembling be sure to cover all holes and vents as to prevent any particles entering. Cover motor with a fine net when mounted.	Again hope warranty is good and pay for express shipping	Must ship back to EMRAX for repair
	8	One P4 motor fails, however the other is still fully functional	System can still run, however it may not be able to hit peak performance targets	5	4	0	9	9	4	Implement safety system to ensure motor is not functioning beyond max rpm boundary	Replace motor, or continue functioning with one motor	Motor is overheating, or functioning improperly.

	#	Potential Failure/Risk	Potential Impacts of Failure/Risk	S	O	D	RPN	Occ. Evaluation	Det. Evaluation	Proactive Risk Treatment	Contingency Plan	Contingency Trigger
Mechanical RA	1	Excessive Torque into RDM	Half shafts/ RDM could break	7	6	5	18	13	11	Preform FEA. Insure that technical specifications of combined motors match the technical specifications of RDM	N/A	N/A
	2	Need to find new RDM and gearbox.	Potential gear ratios not feasible for electric motor. Gearbox cannot be designed/manufactured in time by Pulse	7	7	5	19	14	12	Audi Differential- can buy unit off the shelf but will have no tech support from magna for integration. Can get tech support from MVSL. AAM Differential- 2-Speed differential. Very possible to receive control and mechanical support Pulse Planetary Gearbox- until we receive written confirmation from Pulse, proceed assuming Gearbox will not be feasible	Use stock RDM as an open differential.	No option deemed feasible/available.
	3	Fitting and Mounting either the 1.5 or 2.0 L engines. Mount failure to hold engine or create enough dampening.	Engine gets displaced damaging the drive line. The vehicle has bad vibrations caused by the engine	10	7	5	22	17	12	Perform proper FEA analysis for many different test cases. Also pay close attention to material selection for mount and rubber bushing. Ensure any in house fabrication is done correctly. Seek advice from driveline experts (AAM)	Re-design Engine Mounts and other driveline mounting	Upon noticing that original mounts are not sufficient.
	4	Stock RDM cannot be controlled- need to find replacement part that can be controlled, possible to not find this part	Need to find new part.	7	9	0	16	16	9	Do not consider utilizing the stock RDM in proposed architectures	N/A	N/A
	5	Custom half shafts will be required for the rear axle (differential to wheel shafts). This shaft may not be able to handle the torque output from the motor after the huge gear ratio	Shearing the half-shafts	10	7	0	17	17	7	When we reach the step of looking for a manufacturer to make these shafts for us, clearly communicate the technical specs required and feasibility	Team fabricates half-shafts in house (modification of production vehicle half-shafts)	Upon Failure
	6	Coolant Pump Overload	Insufficient cooling of EV system. Heavy load on coolant pump due to head losses (additional coolant lines/radiators/inverters/motors) could lead to a reduction in coolant flow rate.	4	5	5	14	9	10	Design with a safety margin	Source new coolant pump capable of meeting system load requirements	Upon noticing inadequate cooling of EV system components
	7	Motor to Differential Shaft Failure	Loss of Development Time. Performance Loss	6	4	1	11	10	5	Alignment and Tolerancing taken into account during vehicle development	Re-design component	Upon Failure
	8	Extreme Rear Weight Bias	Packaging HV and power electronic components (Battery, DC/DC, HVJB, HV Charger*) may lead to significant rear weight bias. Vehicle may not pass Saftey Tech	5	5	5	15	10	10	Conduct weight tracking and CG analysis in architecture selection phase of the competition	N/A	N/A
	9	EMRAX Motor: External Rotor	Rotating case of the motor may come into contact with foreign object causing damage to the vehicle or personal injury to occupants and bystanders.	8	6	0	14	14	6	Create casing/ skid plate to enclose the motor	N/A	N/A

	10	Improper shaft	The shaft transferring power can break if installed improperly or motor itself will break	10	2	5	17	12	7	If the shaft is not the provided EMRAX shaft, the motor will not transfer power properly and likely break the and/or the motor	Disassemble and hope that the shaft provided is still viable	Send back to EMRAX to be fixed
Total							403					

APPENDIX E

CAVs System Architecture

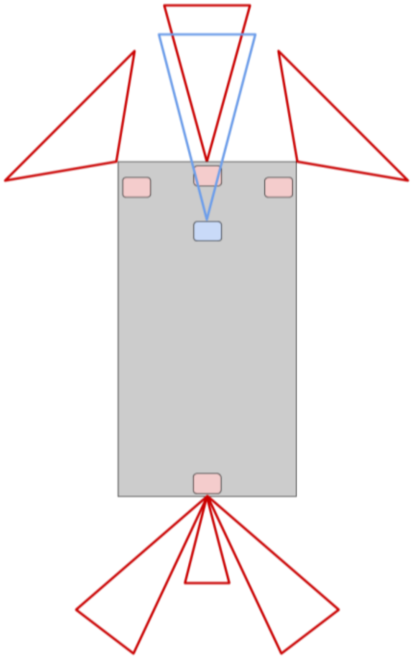


Figure 36: Sensor Layout FOV Model. (Radar - Red | Vision - Blue)

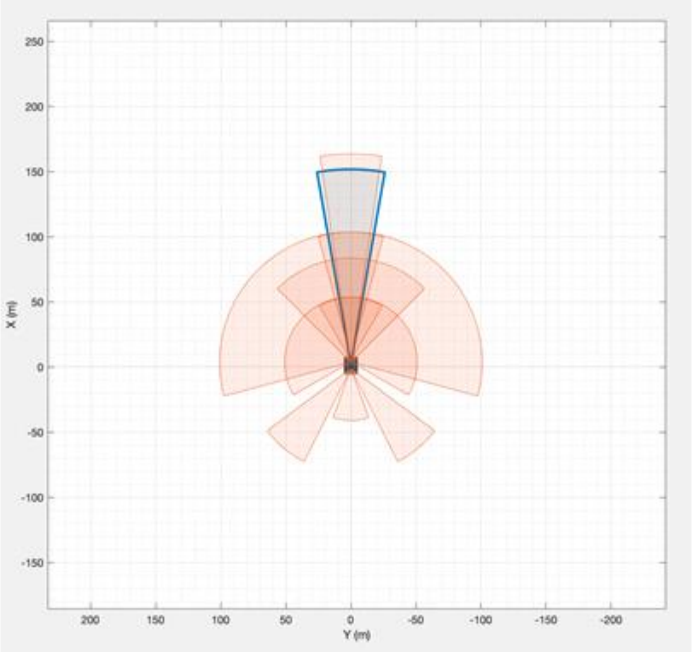


Figure 37: Birds Eye Sensor location and FOV

Figure 38: Side view of front sensor placement on Chevrolet Blazer